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- (54) Title: **ENHANCED FIBER NODES WITH CMTS CAPABILITY**
- (57) Abstract: Enhanced Cable Modem Termination System (CMTS) functionality, including programmable digital dimain modulators and demodulators for dynamic channel assignment, is incorporated into Fiber Nodes (FNs) or mini Fiber Nodes (mFNs), yielding enhanced Fiber Nodes (eFNs). These eFNs distribute CMTS functionality deep into Hybrid-Fiber-Coax Networks (HFCN) rather than centralizing the CMTS functions within a single location. Moving the cable modem terminations closer to the subscribers shortens the analog RF paths required to support cable modems. Communication of both subscriber data and CMTS control data is performed over Ethernet-compatible packet networks between the field-based CMTS and an upstream facility (e.g., the Head End), which includes an Internet gateway. Packet data for multiple subscriber cable modems is easily compressed and merged over common network paths, reducing cabling plant complexity and increasing badwidth utilization. This approach dramatically reduces the indrastructure cost per cable modem. Distributing CMTS functionality among multiple eFNs also reduces demands on already stretched resources at the Head End for space, power, and HVAC. For HFCN channels containing signals with modulation or encoding schemes that are unknown or best processed upstream, the invention also provides for tunneling their spectrum over the same packet network as used for the cable modem data. The channels to be tunneled are isolated using digital receivers, translated to baseband, their data framed, merged with cable modem subscriber data, and transmitted over the packet network. Upstream, the framed channel data is parsed and the original channel spectru, reconstructed to permit information recovery.
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1 **ENHANCED FIBER NODES WITH CMTS CAPABILITY**

2
3 **CROSS REFERENCE TO RELATED APPLICATIONS**

4
5 **[0001]** This application is a Continuation-in-Part of the following patent
6 applications, the disclosures of which are herein incorporated by reference for all
7 purposes:

8 U.S. Patent Application Ser. No. 09/715,992, entitled "METHODS AND
9 APPARATUS FOR TRANSMISSION OF ANALOG CHANNELS OVER
10 DIGITAL PACKET-BASED NETWORKS," Liva et al., filed November 16,
11 2000; and

12 U.S. Patent Application Ser. No. 09/800,397, entitled "TRANSCIVER
13 CHANNEL BANK WITH REDUCED CONNECTOR DENSITY," Alok
14 Sharma, filed March 5, 2001, which in turn claims priority to U.S. Provisional
15 Patent Application Ser. No. 60/187,194, entitled "FREQUENCY AGILE
16 DIGITAL TRANSCIVER BANKS HAVING NON-UNIFORM CHANNEL
17 WIDTH AND REDUCED CONNECTOR DENSITY," Alok Sharma, filed
18 March 6, 2000.

19 **[0002]** This application also incorporates by reference the following patent
20 applications: Docket No. PBC.2000.108, entitled "ENHANCED CMTS FOR
21 RELIABILITY, AVAILABILITY, AND SERVICEABILITY," Liva et al., filed October
22 24, 2001; and U.S. Patent Application Ser. No. 09/974,030, entitled "MULTIPLE
23 INPUT, MULTIPLE OUTPUT CHANNEL, DIGITAL RECEIVER TUNER," Fabien
24 Buda, filed October 10, 2001.

BACKGROUND

[0003] In traditional Hybrid Fiber-Coax (HFC) systems for Cable Television systems, Fiber Nodes (FN) are intermediate sub-systems in an overall information distribution network hierarchy. From least to highest bandwidth concentration, the network hierarchy includes subscribers (generally homes), FNs, secondary hubs (SHs), primary hubs, and the headend.

[0004] FNs interface with the SHs optically and interface with the subscribers over active RF coaxial networks (i.e., networks of coaxial cable interspersed with active RF distribution amplifiers as required for signal integrity). FNs may serve between 600 and 1200 subscribers. This can be accomplished by segmenting the total number of subscribers into "buses" of 300 subscribers. A cascade of five to eight RF amplifiers may exist between the FN and any given subscriber. Four to six fibers may couple the FN to a SH.

[0005] Figs. 1A through 1C illustrate a prior-art HFC cable system having return channels wherein the primary processing is performed at the cable Head End. These return channels can include DOCSIS signals from cable modems and so-called legacy signals, which include conventional analog telephone signals and RF modulated digital signals with proprietary encoding schemes that remain encoded until receipt at the head end. Fig. 1A is a top-level view of the cable system, including the cable system head-end and the customer premises equipment (CPE). Fig. 1B provides additional detail of the CPE of Fig. 1A. Fig. 1C provides additional detail of the NID of Fig. 1B.

[0006] Recent variants to the above HFC architecture have been based on so-called mini fiber nodes (mFNs), a FN variant that is both smaller and deeper into the network (closer to the subscriber) than a traditional FN. Fig. 2A illustrates an HFCN

1 incorporating such mFNs in conjunction with FNs. The mFNs are generally
2 distinguished from FNs in that they interface with only 50 to 100 subscribers and the
3 path from mFN to subscriber is via an all passive coaxial network. The mFN distributes
4 downstream information to the subscribers and aggregates upstream information from
5 subscribers. The mFN interfaces via optical fiber to the next higher level in the
6 hierarchy.

7 **[0007]** There are many possible topologies for mFN-based HFC systems and the
8 exact functionality of an mFN will vary with the system topology. In a first example,
9 MFNs can be used as part of a fiber overlay to upgrade traditional "trunk-and-branch"
10 coaxial systems, or HFC systems with downstream only FNs, with return path (upstream)
11 services (e.g., for Cable Modems). In such applications, the optical return (upstream)
12 path is routed from the mFN directly to the SH, bypassing the downstream only path
13 (which in an HFC system includes FNs). This in effect configures each line extender
14 with a return fiber that provides each passive span with a unique return spectrum. Figs.
15 2A and 2B illustrate such a prior-art HFC cable system having a packet fiber overlay
16 using mini-FiberNodes (mFNs). Fig. 2A is a top-level view of the HFC/mFN cable
17 system. Fig. 2B provides additional detail of the mFNs of Fig. 2A. In a second example,
18 mFNs can be used with "MuxNodes" that replace a single FN or consolidate multiple
19 FNs. MuxNodes not only "distribute" (demultiplex) information downstream but also
20 "aggregate" (multiplex) information upstream (from subscriber to provider).

21 **[0008]** In either architecture – using FNs or mFNs, or a combination of the two –
22 the bandwidth of the upstream path from an FN or mFN has previously been inefficiently
23 utilized. The FN or mFN has heretofore re-transmitted the entire 5-42 MHz return
24 spectrum to upstream hubs, though in most cases only a small portion of that spectrum is
25 actually desired or will be utilized. The entire spectrum has been transmitted upstream

1 because the bulk, cost and power consumption of the equipment required to process the
2 upstream signal and pass on only the desired components has prohibited its deployment
3 in the field.

4 [0009] In previous systems every upstream channel has required a respective
5 splitter tap, receiver input including a bulkhead-mount connector, and cabling between
6 the splitter tap and the receiver input. Such components, especially the high number of
7 connectors, add cost and bulk that would otherwise not be expended, as well as
8 introducing new noise. Additionally, previous systems have required manual
9 adjustments or manual changing of plug-in components, in order to provision or
10 reprovision a channel.

11 [0010] The aforementioned manual configurations of cabling and channel
12 adjustments have been necessary at initial installation and often many times thereafter.
13 Node recombining (e.g., manual recabling to pair a new logical channel with a new line
14 card) has often been necessary whenever an existing subscriber channel reaches capacity
15 and additional channels need to be assigned. Manual channel reprovisioning has also
16 been frequently necessary to avoid various sources of ingress noise, which varies both in
17 time and channels affected.

18 [0011] What is needed is an ability to efficiently process upstream signals in a
19 cost- and space-effective way that can be done close to the subscriber, that reduces
20 hardware-introduced noise and minimizes the need for manual intervention when
21 reprovisioning a channel.

22 [0012] A general discussion of HFC architectures, with a particular focus on
23 mFN-based systems, is provided by the article "HFC architecture in the making: Future-
24 proofing the network," by Oleh Sniezko, et al, in the July 1999 issue of Communications

1 Engineering & Design Magazine (CED Magazine), published by Cahners Business
2 Information, a member of the Reed Elsevier plc group.

3 [0013] "DOCSIS" is a family of interoperability certification standards for cable
4 modems. "OpenCable" is a family of interoperability specifications directly and
5 indirectly related to digital set-top box hardware and software interfaces. "PacketCable"
6 is a family of specifications aimed at facilitating real-time, multimedia packet-based
7 services, using a DOCSIS-managed regional access network as the foundation. While
8 having broad applicability, an initial focus of PacketCable is VoIP (Voice over Internet
9 Protocol). Cable Television Laboratories, Inc. (CableLabs), with offices in Louisville,
10 Colorado, is a research and development consortium of North and South American cable
11 television operators. CableLabs manages, publishes, and distributes a number of
12 specifications and certification standards related to various aspects of Cable Television
13 systems, including the DOCSIS, OpenCable, and PacketCable standards families.

14 [0014] The International Telecommunications Union (ITU), headquartered in
15 Geneva, Switzerland, is "an international organization within which governments and the
16 private sector coordinate global telecom networks and services." The ITU manages,
17 publishes, and distributes a number of international telecom related standards. Standards
18 relevant to Cable Television systems include the ITU-T Series H Recommendations and
19 the ITU-T Series J Recommendations. The "-T" stands for Telecommunications. Series
20 H covers all ITU-T standards for "audiovisual and multimedia systems." Series J covers
21 all ITU-T standards for "transmission of television, sound programme and other
22 multimedia signals."

23

24

25

SUMMARY

- 1
2
- 3 **[0015]** An enhanced CMTS, or “mini-CMTS,” as taught herein, includes
4 programmable digital domain modulators and demodulators that permit dynamic channel
5 assignment. These DOCSIS-compliant CMTSs are characterized by high functional
6 density, a compact form factor, low power consumption, and integral support for the
7 merging of analog and digital channels for transmission over digital packet networks.
- 8 **[0016]** The digital demodulator section of the enhanced CMTS digitizes the
9 entire return spectrum on each of multiple upstream inputs, each of which may include
10 multiple upstream channels with no particular interrelationship. The digitized result is
11 then bussed to the inputs of multiple all-digital receivers. Each receiver demodulator
12 channel may be remotely, automatically, dynamically and economically configured for a
13 particular cable, carrier frequency and signaling baud-rate, from an option universe that
14 includes a plurality of input cables, a plurality of carrier frequencies, and a plurality of
15 available baud-rates.
- 16 **[0017]** Implementing all processing of each upstream channel in digital circuitry,
17 including any baseband translation and filtering for channel selection, minimizes the
18 number of required A/Ds, number and extent of clock sub-systems, bit-width of digital
19 processing stages, and overall complexity. The enhanced CMTS architecture reduces
20 connector density, reduces costs and other bulk components, and improves the system
21 noise performance.
- 22 **[0018]** The enhanced CMTSs are incorporated into Fiber Nodes (FNs) or mini
23 Fiber Nodes (mFNs), yielding enhanced Fiber Nodes (eFNs). These eFNs distribute
24 CMTS functionality deep into Hybrid-Fiber-Coax Networks (HFCN) rather than
25 centralizing the CMTS functions within a single location. Moving the cable modem

1 terminations closer to the subscribers shortens the analog RF paths required to support
2 cable modems. Communication of both subscriber data and CMTS control data is
3 performed over Ethernet-compatible packet networks between the field-based CMTSs
4 and an upstream facility (e.g., the Head End), which includes an Internet gateway.

5 **[0019]** The distributed CMTS and packet network approach has many benefits.
6 The data from multiple cable modems (after being demodulated by the CMTS from the
7 received analog RF) and other upstream sources (to be discussed) is easily compressed,
8 merged, and packet transmitted over common upstream network paths. The downstream
9 data for multiple subscriber cable modems is likewise easily compressed, merged, and
10 packet transmitted over common downstream network paths (for subsequent modulation
11 by the CMTS). The compression, merging, and use of common paths, both reduces
12 complexity and increases bandwidth utilization of the fiber plant, and thus reduces the
13 fiber plant infrastructure cost per cable modem. Distributing CMTS functionality among
14 multiple eFNs also reduces demands on already stretched resources at the Head End for
15 space, power, and HVAC.

16 **[0020]** Dynamic channel allocation (including assignment and configuration)
17 eliminates otherwise time-consuming and costly manual provisioning and re-
18 provisioning of the enhanced CMTSs associated with installation and servicing.
19 Dynamic channel allocation can also dramatically reduce the need to do manual node
20 recombining (prompted by overcapacity situations) or manual channel reprovisioning
21 (prompted by ingress noise). Channel selection and channel characteristics may be
22 configured by transmission of a Channel Table Management Information Block (MIB),
23 supplied over the packet network.

24 **[0021]** Dynamic channel assignment and configuration can be used manually or
25 under programmed control to permit the headend to perform remote spectrum sampling

1 at the eFN, via DSP-based translation, packet-based transmission, and subsequent
2 reconstruction of the original spectra. Such remote sampling has a number of broad
3 applications beyond those previously discussed, including signal monitoring, end-to-end
4 Frequency Division Multiplexing (FDM), telemetry, and remote status monitoring.

5 [0022] More broadly, programmable channel assignment and configuration
6 enables multiple communication channels, unrelated in function or frequency, to be
7 isolated out of a wider spectrum and then efficiently combined and commonly
8 transmitted over a network. The ability to combine multiple diverse streams provides
9 greater functional density and significant savings in power, bandwidth, and cost
10 compared to previous indiscriminate entire spectrum approaches to transmitting analog
11 channels over networks.

12 [0023] In contrast to cable modem signals, which are readily demodulated to
13 extract their underlying data, there are other channels (e.g., certain legacy telephony
14 services) containing signals with modulation or encoding schemes that are unknown or
15 best processed upstream. For these other channels, the invention provides for tunneling
16 their spectrum over the same packet network as used for the cable modem data. It is
17 possible to tunnel upstream only one, or several channels, as desired. If multiple
18 channels are to be tunneled, they need not occupy a contiguous spectrum. The channels
19 to be tunneled are isolated using digital receivers, translated to baseband, their data
20 framed, merged with cable modem subscriber data, and transmitted over the packet
21 network. Upstream, the framed channel data is parsed and the original channel spectrum
22 reconstructed to permit information recovery.

23 [0024] This tunneling approach is particularly advantageous when it is not
24 practical or possible to locally decode a particular channel's spectra within a larger local
25 spectrum due to technical, financial, legal, or other restrictions. Instead of local

1 decoding, the present invention transmits a digitized version of just the desired encoded
2 spectra across a packet network to a remote site where it is practical or possible to
3 perform the decoding. The original signal is then reconstructed and decoded using
4 otherwise legacy methods.

5 [0025] The present invention thus provides a selective and efficient use of
6 available bandwidth, in that it is not necessary to transmit the entire spectrum, when only
7 one or few portions of the spectrum are desired. Furthermore, any or all packet data
8 transmitted between the eFN and an upstream hub or head end may be selectively
9 compressed. Both the selective transmission of upstream channels and the compression
10 of data reduce bandwidth requirements all along the transmission path, contributing to
11 reductions in power, cost, and size of the associated infrastructure.

12 [0026] Example network services compatible with and directly or indirectly
13 supported by the present invention include DOCSIS cable modem (CM) services, VoIP
14 (including compliance with the PacketCable standard) as well as legacy HFC telephony
15 services, NVOD, VOD, compliance with OpenCable standards, and broadcast analog and
16 digital video.

17

18 NOMENCLATURE

19

20 [0027] In the communications industry certain common terms find repeated
21 application at different levels of the design hierarchy and otherwise may be used with
22 varying scope. As a result, it is possible that terms used in this application have multiple
23 context-dependent meanings. Particular attention is required with regard to the terms
24 demodulator, receiver, tuner, and front-end. Those skilled in the art will always be able

1 to readily ascertain the correct meaning from careful study of the text and accompanying
2 drawings.

3

4

Brief Description of Drawings

5

6 **[0028]** Figs. 1A through 1C illustrate a prior-art HFC cable system having legacy
7 return channels. Fig. 1A is a top-level view of the cable system. Fig. 1B provides
8 additional detail of the CPE of Fig. 1A. Fig. 1C provides additional detail of the NID of
9 Fig. 1B.

10

11 **[0029]** Figs. 2A and 2B illustrate a prior-art HFC cable system having a packet
12 fiber overlay using mini-FiberNodes (mFNs). Fig. 2A is a top-level view of the
13 HFC/mFN cable system. Fig. 2B provides additional detail of the mFNs of Fig. 2A.

14

15 **[0030]** Figs. 3A through 3D illustrate an eFN (enhanced Fiber Node), in
16 accordance with the present invention. Fig. 3A is a top-level view of the eFN. Fig. 3B
17 provides additional detail of the DSP Multi-Channel Transceiver ASIC of Fig. 3A. Fig.
18 3C provides detail of the underlying structure for the MAC processor and shared memory
19 of Fig. 3A. Fig. 3D provides additional detail of the Analog Combine and Split
20 Functions of Fig. 3A.

21

22 **[0031]** Figs. 4A through 4E illustrate conceptually the process of digitizing a
23 legacy upstream channel. Fig. 4A shows the 5-42MHz return spectrum, including a
24 desired 6MHz legacy return channel. Fig. 4B represents a low-pass (anti-alias) filtering
25 operation performed in the analog domain. Fig. 4C represents a band-pass (channel

1 isolation) operation performed in the digital domain. Fig. 4D represents a resampling
2 (baseband conversion) operation in the digital domain. Fig. 4E represents a low-pass
3 filter and decimation operation performed in the digital domain.

4
5 **[0032]** Fig. 5 illustrates the layer 2 encapsulation of digitized return channel data.

6
7 **[0033]** Fig. 6 illustrates the layer 3 encapsulation of digitized return channel data.

8
9 **[0034]** Figs. 7A and 7B illustrate the system environment for an HFC cable
10 system having a packet fiber overlay using eFNs, in accordance with the present
11 invention. Fig. 7A is a view that focuses on the relationship between the head-end and
12 the customer premises. Fig. 7B is a view that focuses on the relationship between the
13 cable-system head-end and other networks. Fig. 7C is a view that focuses on the
14 relationship between the eFN and the Master DAC Controller.

15
16 **[0035]** Fig. 8 illustrates an alternate embodiment for an HFC cable system having
17 a packet fiber overlay using eFNs, in accordance with the present invention.

18
19 **[0036]** Fig. 9 provides internal detail of the PDC, Extraction, and Reconstruction
20 block of Fig. 7A.

21
22 **[0037]** Fig. 10 provides internal detail of the Return Channel Reconstruction
23 block of Fig. 9.

24

1 **[0038]** Fig. 11 illustrates the relationship between MAC functions in the MAC
2 processor and shared memory of Fig. 3A.

3

4 **[0039]** Fig. 12 provides internal detail of the downstream transmitter functions
5 implemented on a per-channel basis.

6

7 **[0040]** Fig. 13 illustrates sub-functions of the FEC block of Fig. 12.

8

9 **[0041]** Fig. 14 provides internal detail of the front-end(s) 6000 of Fig. 3B.

10

11 **[0042]** Fig. 15 provides internal detail of the Legacy Digitizing Framer And
12 Return DSP 15 of Fig. 3B.

13

14 **[0043]** Fig. 16 illustrates the DOCSIS-specific return receiver functions
15 implemented on a per-channel basis.

16

17

18

DETAILED DESCRIPTION

System Overview

[0044] Figs. 3A through 3D illustrate what the applicant refers to as an eFN (Enhanced FN), in accordance with the present invention. The eFN is a Fiber Node or mini Fiber Node (mFN) that includes a “mini-CMTS.” As the term is used herein, a mini-CMTS is an enhanced CMTS that is characterized by high functional density, a compact form factor, low power consumption, and integral support for the merging of analog and digital channels for transmission over digital packet networks. The mini-CMTS of the present invention provides a highly compact and cost-effective implementation, including a substantial reduction in the number of bulky connectors required. Additional illustrative detail of various aspects of the eFN and its CMTS is available in the following applications (previously incorporated by reference, above): “ENHANCED CMTS FOR RELIABILITY, AVAILABILITY, AND SERVICEABILITY,” “TRANSCIEVER CHANNEL BANK WITH REDUCED CONNECTOR DENSITY,” and “MULTIPLE INPUT, MULTIPLE OUTPUT CHANNEL, DIGITAL RECEIVER TUNER.”

[0045] Systems of various size and scope that employ eFNs are shown in Fig. 7A, Fig. 7B, Fig. 7C, and Fig. 8. In an illustrative embodiment, in the subscriber direction the eFN interfaces with 50-70 residential subscribers (households passed, HHP) via coaxial RF interface (RF cable). In the headend direction, the eFN interfaces to a Master DAC Controller over a packet network, preferably via fiber. The packet network between the eFN and the Master DAC Controller may be basic, as suggested by Fig. 7C, or more complex, as suggested by Fig. 7B and Fig. 8. Figs. 9 through 16 provide additional detail of various portions of the above mentioned eFN-based systems.

1 **[0046]** In an illustrative embodiment, 100 Mbps Ethernet is used over separate
2 upstream and downstream fibers coupling the Head End (or a Secondary Head End, SH)
3 to each of up to 8 daisy-chained eFNs via respective SONET/DWDM Add/Drop
4 Multiplexers. In a first illustrative embodiment, the mini-CMTS **9000** of each eFN
5 incorporates two downstream (DS) and four upstream (US) channels. These four
6 available selectable US channels are provided by a single physical digitized input. The
7 two DS channels are fully DOCSIS compliant. Two of the available selectable US
8 channels per input are fully DOCSIS compliant and the other two available selectable US
9 channel per inputs support legacy (proprietary) channels.

10 **[0047]** In a second illustrative embodiment, the mini-CMTS **9000** of each eFN
11 incorporates four downstream (DS) and sixteen upstream (US) channels. Four available
12 selectable US channels for each of four physical digitized inputs provide the sixteen US
13 channels. The four DS channels are fully DOCSIS compliant. In a first variation, all
14 four of the available selectable US channels per input are fully DOCSIS compliant. In a
15 second variation, three of the available selectable US channels per input are fully
16 DOCSIS compliant and the other available selectable US channel per input supports a
17 legacy (proprietary) channel.

18 **[0048]** Clearly, as capacity requirements dictate, embodiments having higher rate
19 packet interfaces and additional US and DS channels are readily extrapolated from the
20 first illustrative embodiment. The mini-CMTS is compatible with and directly or
21 indirectly supports analog and digital modulated TV signals, DOCSIS cable modem
22 services, VoIP (based on PacketCable or other standards), compliance with OpenCable
23 standards, legacy telephony and set top boxes.

24 **[0049]** The downstream data received from a regional packet network (or other
25 WAN) via 100 Mbps Ethernet protocol is presented via the mini-CMTS's MAC to the

1 downstream modulator formatted in 188 bytes MPEG frames which are, in turn, coded
2 and modulated into a 44 MHz IF signal. The MPEG stream is compatible with and
3 encapsulates DOCSIS frames.

4 [0050] The analog return spectrum (5-42MHz) is digitized and selected upstream
5 DOCSIS channels are demodulated and the data extracted. The packets are delivered by
6 the DOCSIS MAC to the Ethernet interface and then transferred optically to the Head
7 End (or SH) via the packet network.

8 [0051] Similarly, from the same digitized analog return spectrum (5-42MHz)
9 legacy channels are selected, converted, and packetized into Ethernet frames using either
10 a layer 2 or layer 3 protocol. These frames are forwarded to the cable Head End by
11 commercially available switches. At the Head End, a Master DAC Controller extracts
12 the bit streams from the Ethernet frames and recovers the analog channels. Figs. 4A
13 through 4E illustrate conceptually the process of digitizing a legacy upstream channel.
14 Fig. 5 illustrates the layer 2 encapsulation of digitized return channel data. Fig. 6
15 illustrates the layer 3 encapsulation of digitized return channel data.

16 [0052] This selection of only desired return channels to be forwarded upstream
17 yields a more efficient utilization of US bandwidth.

18

19 Mini-CMTS

20 [0053] Fig. 3A is a top-level view of the eFN. The eFN includes an optical
21 add/drop multiplexer, power extraction and distribution functions, Analog Combine and
22 Split Functions 3D, and the mini-CMTS 9000. The mini-CMTS 9000 is made up of
23 D/As 9020, A/Ds 9010, DSP Multi-Channel Transceiver ASIC 3B, and the MAC
24 Processor and Shared Memory. The mini-CMTS is implemented on a PCB assembly
25 that includes the DSP Multi-Channel Transceiver ASIC (also referred to as the HFC-

1 ASIC), a Media Access Control (MAC) processor and shared memory block, a plurality
2 of D/As, and one or more A/Ds. Fig. 3B provides additional detail of the DSP Multi-
3 Channel Transceiver ASIC of Fig. 3A. Fig. 3C provides detail of the underlying
4 structure for the Mac processor and shared memory of Fig. 3A. The MAC structure
5 includes a micro-controller, a communications controller configured as an Ethernet
6 interface, RAM, non-volatile memory, and a multi-master bus.

7

8 Overview of the Analog Combine and Split Functions

9 [0054] Over the coaxial RF interface, the mini-CMTS supports DOCSIS
10 MAC/PHY services over a number of upstream and downstream channels. The 5-42
11 MHz upstream spectrum from the legacy analog distribution generally includes both
12 DOCSIS channels and legacy channels. This upstream is isolated by appropriate filtering
13 and provided to one or more digitization paths (the optional additional paths being
14 represented via dashed lines in Fig. 3A and Fig. 3D), each digitization path including
15 AGC and A/D circuitry.

16 [0055] Fig. 3D provides additional detail of the Analog Combine and Split
17 Functions of Fig. 3A. In an illustrative embodiment, IF-to-RF upconverters are provided
18 for two digital downstream DOCSIS channels. Optionally, upconverters may be added
19 for one or more legacy broadcast channels. Combiners stack the upconverted channels
20 from the DSP Multi-Channel Transceiver ASIC along with downstream channels
21 originating from the Legacy Analog Coax and Legacy Analog Fiber. Clearly, the
22 upconverters and combiners must meet the constraints associated with eFN usage. In an
23 illustrative embodiment the IF-to-RF upconverters are addressable via an integral I2C
24 industry standard bus and meet the specifications provided in Table 1 through Table 3,
25 below.

Table 1 IF-to-RF Physical Requirements

Parameter	Value(s)
Power Supplies	+5V, +12V
Ambient Temp.	-40 C to +85 C

Table 2 IF-to-RF IF Input Requirements

Parameter	Value(s)
IF frequency	44MHz
Bandwidth	6MHz
Input level	+25 to +35 dBmV
IF attenuator step-size	1 dB (0.1dB preferred)
AGC	enable/disable

Table 3 IF-to-RF RF Output Requirements

Parameter	Value(s)
Frequency	550-870 MHz
Frequency step	50KHz or better
Frequency accuracy	2ppm
Gain control	+45 ~ +61dBmV
Spurious emissions, 50-900MHz	-60dBc
Modulated Adj. Noise, 3.75-9MHz	< -62dBc
Carrier mute	automatic upon frequency change

Overview of the DSP Multi-Channel Transceiver ASIC

[0056] In an illustrative embodiment, the ASIC 3B includes bus interface 6075, transmitter 6050, and receiver 6025. The transmitter and receiver respectively include modulators and demodulators designed to meet the DOCSIS specifications. The receiver also includes processing for legacy return channels.

[0057] The bus interface 6075 provides access to the multi-master bus and thus couples both the transmitter and receiver to the MAC processor and shared memory 11. In the illustrative embodiment of Fig. 3B, a single bus controller is shared by the transmitter and receiver. The transmitter and receiver are shown coupled to the bus controller via interconnect and buffering 9080. Those skilled in the art will recognize

1 that other methods of coupling to the multi-master bus are available and equivalent
2 within the overall context of the present invention.

3 **[0058]** The transmitter includes a number of function blocks common across all
4 channels as well as channel-specific blocks. The common functions include downstream
5 MAC H/W functions **9060** (i.e., those DS MAC functions implemented in hardware) and
6 downstream convergence layer functions **9050**. The downstream MAC H/W functions
7 block **9060** can pass extracted messages for local control **9061** to the upstream MAC
8 H/W functions block **9040**. Multi-channel modulator block **6020** includes a DOCSIS
9 modulator and forward DSP block **12** for each transmit channel. The transmitter receives
10 an MPEG-compatible stream for each channel (two in an illustrative implementation)
11 and delivers a corresponding downstream IF output signal at 44 MHz.

12 **[0059]** The receiver includes a front-end **6000**, channel-specific processing **6010**,
13 a RS decoder and Descrambler **9030**, and Upstream MAC H/W functions **9040**. Fig. 14
14 provides additional detail of Front-end **6000**. Front-end **6000** includes separate front-
15 ends **6005** for each channel. Separate digitized signal outputs are provided for each
16 channel; collectively these outputs comprise signals **1900**. In an illustrative
17 embodiment, at least some channel outputs from **6000** include I and Q quadrature pairs
18 for a given channel. At least one digitized return signal is provided to front-end **6000**. In
19 a preferred embodiment, each of a plurality of provided digitized return signals,
20 corresponding to respective external A/Ds and associated analog input circuits, is
21 selectively coupled to one or more of the individual front-ends **6005**.

22 **[0060]** The front-end channel outputs are provided to the channel-specific
23 processing within block **6010**. These channel outputs generally correspond to both
24 DOCSIS and legacy return channels. Each DOCSIS channel (2 in a first illustrative
25 embodiment) output from the front-end is processed in a DOCSIS Demodulator and

1 Return DSP block **16**. As depicted in Fig. 16, this block provides demodulation of the
2 TDMA upstream transmissions originating from Cable Modems or Set Top boxes. The
3 DOCSIS Demodulator and Return DSP logic **16** provides the MAC layer with channel
4 profile information, including timing, power, and frequency estimation data. The
5 demodulator outputs of each DOCSIS Demodulator and Return DSP block **16** are
6 collectively provided to the RS Decoder and Descrambler **9030**, the output of which is
7 coupled to the Upstream MAC H/W Functions **9040**. The legacy channels (2 in a first
8 illustrative embodiment) output by the front-end are processed in Legacy Digitizing
9 Framer and Return DSP block **15**, the output of which is also coupled to the Upstream
10 MAC H/W Functions **9040**.

11

12 Details of the ASIC Transmitter Functions

13 **[0061]** The Downstream Transmission Convergence (DTC) Layer block **9050**
14 provides an opportunity to transmit additional services, such as digital video, over the
15 physical-layer bitstream. This function provides at its output a continuous series of 188-
16 byte MPEG packets compatible with ITU-T H.222.0, each constituting of a 4-byte header
17 followed by 184 bytes of payload. The header identifies the payload as belonging to the
18 data-over-cable MAC that can be interleaved with other MPEG data flows providing
19 different services. Note that a DOCSIS MAC frame may span over multiple MPEG
20 packets and an MPEG packet may contain multiple DOCSIS MAC frames.

21 **[0062]** The DOCSIS Modulator and Forward DSP block **12** implements the
22 Physical Media Dependent (PMD) functions described in the ITU J.83-B
23 Recommendations with an exception for the interleaving function that must conform
24 only with a subset of the "Level 2" of the ITU recommendation. Fig. 12 provides internal
25 detail of these functions. The first sub-block monitors the MPEG-2 Transport Stream

1 compatible packets and inserts a parity checksum for detected sync bytes (1st byte
2 having a value of 47 HEX) to provide error detection capability and packet delineation.

3

4 Forward Error Correction

5 [0063] Fig. 13 illustrates the sub-functions of the Forward Error Correction
6 (FEC) block of Fig. 12. The Reed-Solomon encoder implements an RS(128,122,3) code
7 over GF(128). It provides encoding to correct up to 3 RS symbol (7-bit size) per RS
8 block of 128 symbols.

9 [0064] The next FEC sub-block is a convolutional type interleaver supporting
10 variable depth $I=128, 64, 32, 16$, and 8. It evenly disperses the symbols, protecting
11 against a burst of symbol errors from being sent to the RS decoder at the receiver side. A
12 frame synchronization sequence trailer delineates the FEC frame in order to provide
13 synchronization for RS decoding, de-interleaving as well as de-randomizing at the
14 receiver side. Four data bits are transmitted during the FEC frame sync interval in order
15 to convey the interleaving parameters to the receiver. Note that the sync trailer depends
16 on the modulation format.

17 [0065] Next a synchronous randomizer provides for even distribution of the
18 symbols in the constellation. The randomizer is initialized during the FEC frame trailer
19 and enabled at the first symbol after the trailer; thus the trailer is not randomized.

20 [0066] The Trellis Encoder uses an overall code rate of 14/15 with 64-QAM and
21 19/20 with 256-QAM. It is based on a 1/2 -rate binary convolutional encoder punctured
22 to 4/5 rate. In 64-QAM mode, 28 bits are collected in block, coded and mapped to 5x 64-
23 QAM symbols. In 256-QAM mode, 38 bits feed the trellis encoder and deliver 40 bits
24 that are mapped to 5x 256-QAM symbols. Note that the trellis-coding scheme used is 90°

1 (90-degree) rotationally invariant to avoid FEC resynchronization in the receiver after
2 carrier phase slips.

3

4 QAM Modulator

5 [0067] The 64- or 256-QAM symbols at the trellis encoder output of the FEC
6 Encoder are pulse shaped using square-root raised cosine Nyquist filtering before
7 modulation around a selected RF carrier. The roll-off factor is $\alpha=0.18$ for 64-QAM and
8 $\alpha=0.12$ for 256-QAM. The channel spacing (bandwidth) is 6 MHz, which leads to a
9 symbol rate of 5.057 Mbaud with 64-QAM and 5.36 Mbaud with 256-QAM. The RF
10 frequency band is 91 to 857 MHz. In practice, the modulation is first performed using an
11 IF stage with a standard IF frequency at 43.75 MHz (36.15 in Europe), and next the
12 signal is up-converted from IF to RF using an up-converter function.

13

14 Overview of DOCSIS Receive Functions

15 [0068] The upstream receiver 6025 incorporates all the upstream functions
16 required to implement the DOCSIS Physical Media Dependent (PMD) sub-layer. The
17 receiver extracts the data packets transmitted by the Cable Modems (CMs) and sends
18 them to the MAC layer. If the concatenation / fragmentation function is used, the data
19 packets delivered by the upstream receiver are fragment payloads of MAC frames. If not,
20 the data packets are full DOCSIS MAC frames. The upstream receiver is a multiple
21 channel burst receiver supporting for each burst: a variable burst length (0-255
22 minislots), flexible modulation scheme (QPSK, 16-QAM), variable symbol rate (5 values
23 from 160 to 2560 kbaud), variable preamble length and value, variable randomizer seed,
24 and programmable FEC. Each upstream receiver channel is provisioned appropriately
25 for each of these parameters via the management and control functions of the MAC

1 layer. In addition, the upstream receiver integrates channel performance and monitoring
2 function that feeds the MAC layer with all the necessary information for ranging
3 purposes and for channel capacity optimization.
4

5 Front-End

6 [0069] The front-end 6000 down-converts each channel signal to baseband, filters
7 the down-converted signal using a matched filter (roll-off factor $\alpha=0.25$), and performs
8 synchronization in timing and frequency. Additional illustrative detail of a front end is
9 available in the following application (previously incorporated by reference, above):
10 "MULTIPLE INPUT, MULTIPLE OUTPUT CHANNEL, DIGITAL RECEIVER
11 TUNER."
12

13 Burst Demodulator

14 [0070] Each QPSK or QAM burst modulated channel signal is then demodulated
15 within a respective DOCSIS demodulator and Return DSP block 16 in order to extract
16 the data transmitted within the burst. The demodulator may also equalize the signal
17 before its decision circuit in order to compensate for echoes and narrow-band ingress
18 noise. Gain control and power estimation functions are necessarily provided to insure
19 correct demodulation. Each DOCSIS demodulator and Return DSP block 16 delivers at
20 its output one or more FEC scrambled packets.
21

22 Descrambler and FEC Decoder

23 [0071] The operation of RS Decoder and Descrambler block 9030 is now
24 examined. At the beginning of each data burst, the register of the de-scrambler is cleared
25 and the seed value is loaded. The de-scrambler output is combined in a XOR function

1 with the data. Next, the information data is separated into FEC codewords and decoded,
2 where the FEC is an RS (k, n, T) with $k=16$ to 253 , $n=k+2T$ and $T=0, 10$. $T=0$ means the
3 FEC is turned off. Note that the last codeword can be shortened and thus, the RS decoder
4 must fill the codeword with the necessary number of zeros before decoding. Finally, the
5 decoded data is fed to the MAC layer.

6

7 Performance Monitoring

8 [0072] In an illustrative embodiment, the upstream receiver also provides the
9 following per-channel performance information to the MAC layer:

- 10 a) Timing estimation;
- 11 b) Frequency offset estimation;
- 12 c) Power estimation (signal and noise);
- 13 d) Pre-equalizer taps estimation;
- 14 e) BER estimation (preamble and FEC);
- 15 f) Collision indication;
- 16 g) Missed acquisition of burst (due collision or noise); and
- 17 h) RF Spectrum monitoring.

18

19 Legacy Upstream Channel Digitizer Functions

20 [0073] Figs. 4A through 4E illustrate conceptually the process of digitizing a
21 legacy upstream channel. (The understanding of this discussion is facilitated by
22 examination of Fig. 3A, Fig. 3B, Fig. 3D, Fig. 14.) Fig. 4A shows the 5-42MHz return
23 spectrum, including a desired 6MHz legacy return channel. Fig. 4B represents a low-pass
24 (anti-alias) filtering operation performed in the analog domain (see also Fig. 3D) to
25 eliminate out of band noise and unwanted signals. Subsequently, one of the provided

1 A/Ds (see reference **9010** in Fig. 3A) digitizes the entire return spectrum in the Nyquist
2 space.

3 **[0074]** Once digitized, the desired legacy signal needs to be converted to
4 baseband, isolated from other upstream signals, and decimated. Figs. 4C through 4E
5 illustrate these functions conceptually. Fig. 4C represents a band-pass (channel isolation)
6 operation performed in the digital domain at the provisioned frequency and bandwidth,
7 as directed by the MAC control functions. As illustrated in Fig. 4D, the signal is then
8 resampled, converted to baseband, and decimated by a multistage decimation process.
9 The data is subsequently digitally filtered, as illustrated in Fig. 4E, to eliminate unwanted
10 spectra-replicas. In an illustrative embodiment, the digitized legacy signal is baseband
11 converted prior to isolation and decimation. As represented in Fig. 14, these functions
12 are performed for each channel by a respective block **6005**, within front-ends **6000**.

13 **[0075]** The digital baseband signal is then sent to the Upstream MAC H/W
14 Function block **9040** via Legacy Digitizing Framer and Return DSP block **15**. In the
15 Mac layer the digitized baseband stream is organized into Ethernet frames. Legacy
16 Digitizing Framer and Return DSP **15** facilitates the framing process, including the
17 identification of each frame by eFN-ID, channel-ID and Payload control (using Source
18 Address, SA; and Destination Address, DA). Legacy Digitizing Framer and Return DSP
19 **15** also provides the MAC layer with user profile information, including power and
20 frequency estimation data.

21 **[0076]** At the Head-end, as shown in Fig. 7A, Fig. 9, and Fig. 10, a reverse
22 process (discussed in detail below) performs extraction and reconstruction of an exact
23 replica of the legacy signal(s) both in frequency position and bandwidth. The
24 reconstructed signals may then be submitted to the appropriate legacy equipment for
25 demodulation and data retrieval. This combination of digitization, framing, and

1 integration with other upstream packet traffic in accordance with the present invention,
2 does not increase the complexity of the upstream receivers and provides a substantial
3 reduction in data transfer requirements (e.g., by a factor of 10) compared to digitizing the
4 entire upstream spectrum.

5

6 MAC Layer Functional Overview

7 [0077] In an illustrative embodiment, the eFN of Fig. 3A implements all the
8 MAC functions interfaces required to be fully compliant with DOCSIS. The eFN is
9 intended to be software upgradeable for present and future versions of DOCSIS. MAC
10 layer functions beyond those required by DOCSIS are also provided to support at least
11 two Legacy channels, with respective MIBs and Messages.

12 [0078] Fig. 11 illustrates the MAC functions performed by the MAC Processor
13 and Shared Memory. These functions include: PHY configuration and monitoring; de-
14 fragmentation, de-concatenation, and decryption; MAC management; CM management;

15 [0079] Service Flow (SF) management; scheduler; RF management; Upstream
16 (US) and Downstream (DS) Classifier; Upstream (US) and Downstream (DS) Payload
17 Header Suppression (PHS); encryption; security based on the DOCSIS Baseline Privacy
18 [BPI] and Baseline Privacy Plus [BPI+] specifications; DOCSIS DS frame generation;
19 and CMTS MAC system management.

20 [0080] DOCSIS requires the mini-CMTS to support various functions and
21 protocol layers above the MAC sublayer. These are listed in table 4, below.

22

23

24

Table 4 DOCSIS functions implemented in an illustrative embodiment

Function Type	Examples within Type
Forwarding and filtering	Layer 2 Packet Forwarding, Packet Filtering
Network-layer protocols	IGMP, ICMP
Higher-layer functions	TFTP, DHCP, TOD, RSVP, RTP, COPS, DNS, RADIUS
CMTS management	CM Directory, SNMP, CLI
Network Side Interface (NSI)	WAN and MPEG interfaces

[0081] The mini-CMTS is required to perform the following functions as part of managing itself: initialization and power on self-test; fault and performance monitoring; diagnostics; alarming via LEDS and the command line interface; and background maintenance functions.

Microprocessor and Transport Interfaces (Ethernet I/F)

[0082] Fig. 3C provides detail of the underlying structure for the MAC processor and shared memory of Fig. 3A. The strict physical limitations of the eFN require a solution that is low-power and highly integrated, but capable of supplying the significant computational horsepower and I/O bandwidth required by the Real Time Operating System (RTOS) and MAC functionality. In an illustrative embodiment, a Motorola MPC8260 PowerQUICC II is used. This versatile communications processor integrates on to a single chip a high-performance PowerPC RISC microprocessor, a very flexible system integration unit, and multiple communication peripheral controllers. The latter are configured as Ethernet interfaces for communication with the cable system Head End.

[0083] The MPC8260 includes an EC603e, an embedded variant of the PowerPC 603e microprocessor having no floating-point processor. The EC603e includes 16KB of level-one instruction cache and 16KB of level-one data cache. Software running on the

1 EC603e implements the following functions: ranging; registration; UCD message
2 generation UCC, BPKM, and DSx protocol processing; and MAP message generation.

3 [0084] The MPC8260 further includes an integrated communications processor
4 module (CPM), which is an embedded 32-bit processor using a RISC architecture to
5 support several communication peripherals. The CPM interfaces to the PowerPC core
6 through an on-chip 24Kbyte dual-port RAM and DMA controller. Using a separate bus,
7 the CPM does not affect the performance of the PowerPC core. The CPM handles the
8 lower MAC layer tasks and DMA control activities, leaving the PowerPC core free to
9 handle higher MAC layer and ASIC related MAC activities. More specifically, the CPM
10 implements the following functions: downstream/upstream Classifier, PHS, traffic
11 shaping, forwarding and filtering. The CPM contains three fast communication
12 controllers (FCCs), each including support for a 10/100-Mbit Ethernet/IEEE 802.3
13 CDMS/CS interface through a media independent interface. Two 100Mbps Ethernet
14 interfaces are implemented in this manner, for the packet communications with the cable
15 system Head End.

16 [0085] The MPC8260 further includes a system interface unit (SIU), which
17 includes a flexible memory controller usable with many memory system types (e.g.
18 DRAM, FPD RAM, SDRAM, etc...), a 60x bus, a programmable local bus, and the on
19 chip communications processor module. In an illustrative embodiment, PC66 SDRAM
20 is used for the main memory. There are three memory types used in the illustrative
21 embodiment. As shown in Fig. 3C, a 4MB SDRAM is attached as local RAM, between
22 16 and 64MB of SDRAM is attached to the multi-master 60x bus as shared RAM, and
23 between 8 and 32MB of Flash memory is coupled (via buffers) to the multi-master 60x
24 bus, as shared NV Memory. The 4MB SDRAM operates at 66MHz, is 32-bits wide, and
25 is intended for use exclusively by the CPM to buffer descriptors for the communication

1 channels or raw data that is transmitted between channels. The 16-64MB SDRAM
2 operates at 66MHz, is 64-bits wide, and is intended for use by either the EC603e or bus
3 mastered accesses by the DSP Multi-Channel Transceiver ASIC. The 8-32MB Flash
4 includes storage for the operating system and applications. All memory is soldered down
5 to the supporting PCB to improve reliability.

6 [0086] In an illustrative embodiment, a front-side bus, level two, (FSB L2) cache
7 is used in conjunction with the MPC8260. An MPC2605 integrated secondary cache
8 device is used. The MPC2605 is a single chip, 256KB integrated look-aside cache with
9 copy-back capability. The MPC2605 integrated data, tag, and host interface uses
10 memory with a cache controller to provide a 256KB level 2 cache. At 66MHz, the
11 MPC2605 supports zero wait state performance and 2-1-1-1 burst transfers. Without the
12 optional cache, an auxiliary PowerPC processor may be necessary to provide the needed
13 computational capability of the MAC functions.

14 [0087] The interface between the MAC Processor and the DSP Multi-Channel
15 Transceiver ASIC is the 60x bus. This bus interface supports 66MHz operation, 64-bit
16 wide data path, burst transfers and bus mastering arbitration. The MPC8260 is
17 configured for "60x compatible mode" and not "Single bus mode". Configured in this
18 mode, the MPC8260 can support one or more bus masters and the level-two cache. The
19 60x bus is used in pipeline mode for increased performance, requiring some additional
20 external logic.

21

22 Optical Network and Ethernet Interface.

23 [0088] Fig. 3A and Fig. 3C are relevant to the following discussion of the
24 Optical-to-Electrical (O/E) interface. The CPM of the MPC8260 couples to the O/E
25 interface via an LX970A (a product of Level One, Inc.). The LX970A is a 10/100Mbps

1 Fast Ethernet PHY Transceiver that provides a Media Independent Interface (MII) for
2 attachment to the CPM and a pseudo-ECL interface for use with 100BASE-FX fiber
3 modules to the Head End fiber interface. As shown in Fig. 3A, three fibers provide
4 connectivity between the eFN and the SH (and/or Head End). Each fiber carries up to
5 several wavelengths corresponding to various downstream channels or upstream bursts
6 from multiple eFNs.

7

8

9 Other Features of the Mini-CMTS

10 [0089] In an illustrative embodiment the following features further characterize
11 the eFN's mini-CMTS:

- 12 a) fully digital downstream implementations of Annex B coding and modulation;
- 13 b) fully digital upstream implementation of DOCSIS modulated upstream channels,
14 including direct IF sampling, digital baseband conversion, and parallel
15 demodulation of at least 2 channels;
- 16 c) parallel digitization of 2 frequency bands containing at least 2 legacy packetized
17 digital return channels (PDC);
- 18 d) frequency agility in the total upstream band;
- 19 e) fully flexible receiver to allow performance optimization vs. noise and
20 intersymbol interference (all DOCSIS channel parameters, burst profiles & user
21 profiles), with features including variable symbol rate, variable burst length,
22 Reed-Solomon decoding with variable error correction capability and variable
23 code rate, and both QPSK & 16-QAM demodulation (with extensions to 32- &
24 64-QAM); and
- 25 f) accurate power, timing & carrier offset estimation.

- 1 **[0090]** In preferred embodiments, the eFN's mini-CMTS is further compatible
2 with and supports the following cable-modem features:
- 3 a) fully digital, non-data aided symbol clock recovery;
 - 4 b) joint blind and decision-directed channel equalization;
 - 5 c) fully digital carrier phase/frequency recovery;
 - 6 d) fast and aliasing free frame lock technique;
 - 7 e) transform based area/timing efficient extended Reed-Solomon decoder;
 - 8 f) single cycle Galois field arithmetic elements (inverters, multipliers,
9 adders/subtractors);
 - 10 g) digital carrier synthesis supporting on-the-fly frequency selection;
 - 11 h) variable rate interpolator supporting multiple upstream symbol rates; and
 - 12 i) adjustable transmit level and local time reference.

13
14
15

16 System Environment

- 17 **[0091]** Figs. 7A and 7B illustrate the system environment for an HFC cable
18 system having a packet fiber overlay using eFNs, in accordance with the present
19 invention. Fig. 7A is a view that focuses on the relationship between the head-end and
20 the customer premises. Fig. 7B is a view that focuses on the relationship between the
21 cable-system head-end and other networks. Fig. 8 illustrates an alternate embodiment for
22 an HFC cable system having a packet fiber overlay using eFNs, in accordance with the
23 present invention.

24
25

1 Logical Allocation of Upstream Channels

2 [0092] An upstream channel can be logically allocated to any of the four
3 available selectable upstream channels per digitized input. One approach to avoiding
4 physical node recombining, where capacity growth is expected, is to initially turn on only
5 one upstream channel per digitized input. If the initial channel reaches capacity, then
6 another channel can be provisioned using the dynamic channel allocation capabilities of
7 the mini-CMTS.

8 [0093] This ability to logically assign channels has a number of benefits. There
9 is no need to purchase a CMTS line card, chassis, or channel bank every time an
10 upstream port reaches capacity. Headend technician time is not lost installing new
11 hardware, disconnecting and reconnecting cables, and reconfiguring the system.
12 Misconfigurations or service disruptions common to physical recombining are avoided.
13 Recombining instead is an operation that can be performed both remotely and online.
14 Finally, channels can be dynamically assigned for specific services or functions, such as
15 migration between different revisions of cable modem standards.

16

17 Dynamic Channel Allocation

18 [0094] In addition to the benefits of reducing installation labor and avoiding
19 physical node recombining, dynamic channel allocation also provides a solution to
20 ingress noise, which can vary both in time and channels affected. In conjunction with real
21 time spectral analysis of the entire return spectrum and continuous feedback monitoring
22 of customer quality of service (QoS) levels, the mini-CMTS can quickly detect a problem
23 and take a variety of actions.

24 [0095] Specific actions that the mini-CMTS can take in response to a detected
25 problem include: scanning the entire return spectrum in real time to analyze the

1 environment and find "clean" spectrum; resize the affected channel; dynamically
2 increase or decrease bandwidth; move the channel to a new carrier frequency; allocate
3 and additional channel; move one or all cable modems from one channel to another
4 without registering. Because the modems can be dynamically switched without having
5 to re-register, the integrity of service level agreements are preserved for mission-critical
6 services such as VoIP calls and symmetrical business services.

7

8 Reconstruction of Legacy Upstream Channels at the Head End

9 [0096] In order to assure proper demodulation of the legacy return signals, it is
10 necessary to reconstruct each upstream signal precisely at its original carrier frequency.
11 Fig. 10 provides detail of this process. The context for these functional blocks includes
12 Fig. 9 and Fig. 7A.

13 [0097] Reconstruction of the original signal requires performing steps that are the
14 reverse of the sampling and decimation process performed in the mini-CMTS of the eFN.
15 Based on information either known in advance (e.g., the decimation ratio provisioned for
16 the channel) or included in the Ethernet encapsulated frames (the eID, CID, CTRL and
17 SEQ parameters; describing the upstream signal origin, BW and frequency), it is
18 straightforward to reconstruct and upsample to generate an exact replica of the digitized
19 sample stream provided to the front-end of the eFN's mini-CMTS.

20 [0098] These samples are fed into a D/A converter whose clock is running
21 synchronously to the A/D converter in the eFN. The reconstructed signal is thus placed
22 precisely on the proper carrier frequency. The required clock synchronicity can be
23 achieved by a number of means, including e.g. FIFO fullness control and timestamp
24 messaging. The particular method of clock synchronicity is determined at least in part by

1 the degree of short-term absolute frequency precision required by the legacy
2 demodulator/receiver equipment.

3 [0099] Fig. 9 and Fig. 7A provide additional detail showing how multiple
4 instances of the Return Channel Reconstruction logic 10 are implemented within the
5 Master DAC Controller 9, at the Head End. The Master DAC Controller 9 provides
6 extraction and reconstruction of each packetized digital return channel (PDC). Each
7 legacy signal is reconstructed independently and delivered to a corresponding receiver.
8 It is also possible to combine several analog reconstructed signals for delivery over a
9 single coaxial cable to a common legacy demodulator/receiver.

10

11 End-to-End Operation of the Packetized Digital Return Channel (PDC)

12 [0100] In conjunction with the A/D(s) 9010 and front-ends 6000, a Legacy
13 Digitizing Framer and Return DSP 15 (located inside each of multiple mini-CMTSs)
14 isolates digitized return channels specified by the Master DAC Controller 9 (located at a
15 cable Head End or SH), encapsulates the associated bit stream into Ethernet packets, and
16 transmits the packets over the regional packet network. (The digitization and packet
17 encapsulation formats are described below.) These packets are forwarded to the
18 distribution hubs and Head End. Since these packets are encapsulated using an Ethernet
19 frame format, standard switches (and routers) can be used to aggregate and relay the
20 traffic.

21 [0101] At the Head End, the Master DAC Controller 9 extracts the bit streams
22 from the Ethernet frames and recovers the analog channels. The Master DAC Controller
23 9 also controls and monitors the Legacy Digitizing Framer and Return DSP 15 within
24 each of multiple remote eFNs. In an illustrative embodiment, the Master DAC
25 Controller 9 can control up to 216 Digitizing Framers.

1 **[0102]** Each framer is assigned an IP address and a 16-bit unique identifier (eFN
 2 Station ID). The Master DAC Controller 9 communicates with the framers via SNMP.
 3 At initialization, the Master DAC Controller configures the framer to select different
 4 channels. In an illustrative embodiment, each Legacy Digitizing Framer and Return DSP
 5 15 is capable of supporting four analog channels. The channels can be configured
 6 independently. However, these channels should not overlap in frequency. The
 7 Characteristics of each Packetized Digital Return Channel (PDC) are given in Table 5,
 8 below.

9

Table 5 Channel Characteristics

Characteristic	Definition
Channel ID	a unique 16-bit identifier specifying the channel
Frequency	the center frequency of the channel, in Hertz
Width	the bandwidth of the channel, in Hertz
Frame Length	number of data bytes in each frame
Resolution	number of bits per analog sample

11

12

13 **[0103]** Each frame/packet is uniquely identified by the fields shown in Table 6,
 14 below.

15

Table 6 Frame Field Definitions

Field	Length	Description
eID (or IP addr)	16 bits	eFN Station ID
CID	8 bits	Channel ID
CTRL	8 bits	Control
SEQ	16 bits	Sequence Number

16

17

1 Data Encapsulation for the Packetized Digital Return Channel

2 **[0104]** Within the eFN's mini-CMTS, the selected analog channels are digitized
3 into streams of bits. These bits are encapsulated into frames. In an illustrative
4 embodiment, the Digitizing Framer provides both a Layer 2 encapsulation mode and a
5 Layer 3 encapsulation mode.

6 **[0105]** Since Layer 2 frames carry only LAN address information, only switches
7 and transparent bridges can forward them. Therefore, regular IP routers cannot be used
8 to forward the Layer 2 frames at the distribution hubs and Head End, as these frames do
9 not have any IP information. The advantage of using Layer 2 encapsulation is bandwidth
10 efficiency. Since the frames do not have any IP/UDP headers, the framing is very
11 efficient especially for short packets. The amount of overhead per frame is 26 bytes
12 (Ethernet) + 6 bytes (PDC) = 32 bytes.

13 **[0106]** Since Layer 3 frames are encapsulated in UDP packets, they are
14 forwarded and routed using standard switches and routers. This would allow the Master
15 DAC Controller to be located at different IP subnets. With Layer 3 encapsulation, the
16 amount of overhead per frame is 26 bytes (Ethernet) + 20 bytes (IP) + 8 bytes (UDP) =
17 54 bytes.

18

19 Layer 2 Encapsulation

20 **[0107]** Implementation of a "best efforts" upstream data channel using point-to-
21 point layer 2 protocol is summarized as follows. The 5-42 MHz US spectrum is
22 digitized, filtered and decimated to provide a data stream corresponding to the desired
23 channel. The data stream is packetized in Ethernet frames and transmitted using layer 2
24 protocol to the Master DAC controller 9 (located in the Head End). Each frame is
25 identified by eFN-ID, channel-ID and Payload control (using SA and DA). The Master

1 DAC Controller 9 will reconstruct the original legacy signal(s) at the Head End (with the
2 original frequency and bandwidth). The Master DAC Controller 9 will provide the
3 resulting legacy flows to legacy equipment for subsequent demodulation. Also using
4 layer 2 protocol over the downstream path, the Master DAC Controller 9 sends control
5 commands to specific eFNs as required to implement provisioning and configuration of
6 each eFN's mini-CMTS.

7

8 **[0108]** With Layer 2 encapsulation, the bit streams are encapsulated into Ethernet
9 frames as shown in Fig. 5. The source address and destination address of the frames are
10 the hardware addresses of the Digitized Framer and Master Controller, respectively. A
11 Packetized Digital Return Channel (PDC) header is inserted to uniquely identify each
12 frame. The PDC header includes four fields: eID is the eFN Station ID of the associated
13 Framer, CID is the Channel ID of the analog channel and CTRL contains control bits and
14 reserved bits. SEQ is the byte sequence number and identifies the byte in the stream of
15 data from the Framer to the Master Controller that the first byte of data in this frame
16 represents.

17

18 Layer 3 Encapsulation

19 **[0109]** Implementation of a "best efforts" upstream data channel using a point-to-
20 point UDP/layer 3 protocol is summarized as follows. The 5-42 MHz US spectrum is
21 digitized, filtered and decimated to provide a data stream corresponding to the desired
22 channel. The data stream is encapsulated in UDP packets and transmitted using layer 3
23 protocol to the Master DAC controller 9 (located in the Head End). Each frame is
24 identified using the source port number (eFN-ID, channel-ID and Payload control). The
25 Master DAC Controller 9 will reconstruct the original legacy signal(s) at the Head End

(with the original frequency and bandwidth). The Master DAC Controller 9 will provide the resulting legacy flows to legacy equipment for subsequent demodulation. Using TCP, the Master DAC Controller 9 also sends control commands from the Head End Management System (HMS) to specific source port numbers in order to implement provisioning and configuration of each eFN's mini-CMTS.

[0110] With Layer 3 encapsulation, the bit streams are encapsulated in UDP packets as shown in Fig. 6. In the IP header, the source IP address and the destination IP address are the IP addresses of the transmitting framer and the Master Controller, respectively. The source UDP port number (SP) is used to represent CID and CTRL while the default destination UDP port number is 3103. Since the packet size is constant (set by SNMP), the UDP packet length field is used to represent the SEQ field.

Control and Monitoring of Legacy Digitizing Framer

[0111] The parameters for each channel's framer are configured via SNMP. The attributes for each analog channel are detailed in Table 7, below.

Table 7 Channel Table MIB

MIB	Access	Syntax	Description
Channel Id	RW	Integer32 (0..255)	Identifier of this channel
Frequency	RW	Integer32 (0..1 000 000 000)	Center frequency of this channel in Hertz
Width	RW	Integer32 (0..10 000 000)	Bandwidth of this channel in Hertz
Power	RO	Integer32	Received Power in tenth of dBmV
Length	RW	Integer32 (64..1518)	Length of Packets in Bytes
Resolution	RW	Integer32 (8..12)	Number of Bits per analog sample

1 [0112] Since SNMP is a best effort delivery protocol, the Master DAC controller
2 is responsible for guarantying the retrieval of the setting of the channel attributes. An
3 ARQ approach is used to ensure the framers are configured with the correct setting:

```
4  
5        While (true) {  
6            Configure the Framer using SNMP SET  
7            Read the configuration of the Framer via SNMP GET  
8            If (Correct setting)  
9                Break  
10            Wait a few seconds  
11        }  
12
```

13 In the above approach, the DAC controller would repeatedly transmit SNMP SET
14 commands until the corresponding channel is set up correctly.

15

1 CONCLUSION

2

3 [0113] Although the present invention has been described using particular
4 illustrative embodiments, it will be understood that many variations in construction,
5 arrangement and use are possible consistent with the teachings and within the scope of
6 the invention. For example, interconnect and function-unit bit-widths, clock speeds, and
7 the type of technology used may generally be varied in each component block of the
8 invention. Also, unless specifically stated to the contrary, the value ranges specified, the
9 maximum and minimum values used, or other particular specifications (such as the
10 frequency ranges for upstream signals; the content type, modulation and encoding
11 schemes of the upstream signals; the type of microprocessor utilized), are merely those of
12 the illustrative or preferred embodiments, can be expected to track improvements and
13 changes in implementation technology, and should not be construed as limitations of the
14 invention.

15 [0114] Functionally equivalent techniques known to those skilled in the art may
16 be employed instead of those illustrated to implement various components or sub-
17 systems. It is also understood that many design functional aspects may be carried out in
18 either hardware (i.e., generally dedicated circuitry) or software (i.e., via some manner of
19 programmed controller or processor), as a function of implementation dependent design
20 constraints and the technology trends of faster processing (which facilitates migration of
21 functions previously in hardware into software) and higher integration density (which
22 facilitates migration of functions previously in software into hardware).

23 [0115] All such variations in design comprise insubstantial changes over the
24 teachings conveyed by the illustrative embodiments. The names given to interconnect
25 and logic are illustrative, and should not be construed as limiting the invention. It is also

1 understood that the invention has broad applicability to other communications
2 applications over distributed networks, and is not limited to the particular application or
3 industry of the illustrated embodiments. The present invention is thus to be construed as
4 including all possible modifications and variations encompassed within the scope of the
5 appended claims.
6

1 We claim:

2

3 1. A fiber node for deployment in a hybrid fiber-coax network (HFCN) at an
4 intermediate point between an upstream HFCN facility and a plurality of subscriber
5 cable modems, the fiber node comprising:

6 a) a packet protocol block having a packet data interface, a transmitter data
7 interface, and a receiver data interface, said packet protocol block
8 communicating subscriber cable modem data with said upstream HFCN
9 facility via said packet data interface;

10 b) a plurality of modulators transmitting data to said subscriber cable modems
11 via a downstream analog RF interface, said transmitted data being provided
12 by said packet protocol block via said transmitter data interface; and

13 c) a plurality of demodulators for extracting data from subscriber cable modems
14 received via an upstream analog RF interface, said extracted data being
15 provided to said packet protocol block via said receiver data interface.

16

17 2. The fiber node of claim 1, wherein the cable modems are compatible with the
18 DOCSIS standard.

19

20 3. The fiber node of claim 1, wherein the upstream facility is a head end.

21

22 4. The fiber node of claim 1, wherein the upstream facility is a secondary head end.

23

24 5. The fiber node of claim 1, wherein the upstream facility is a hub.

25

- 1 6. The fiber node of claim 1, wherein channel separation is performed prior to the
2 demodulators such that multiple channels are extracted from each physical
3 transmission path of the upstream analog RF interface.
4
- 5 7. The fiber node of claim 1, further including at least one digitizing framer for
6 digitizing modulated signals as received via an upstream analog RF interface, said
7 digitized modulated signal data being provided to said packet protocol block via said
8 receiver data interface.
9
- 10 8. The fiber node of claim 7, wherein the cable modems are compatible with the
11 DOCSIS standard and the modulated signals are legacy telephone signals.
12
- 13 9. The fiber node of claim 7, wherein the extracted data and the digitized modulated
14 signal data are merged in said packet protocol block for communication over a
15 common packet transmission path with the upstream facility.
16
- 17 10. The fiber node of claim 8, wherein the extracted DOCSIS cable modem data and the
18 digitized legacy telephone data are communicated with said upstream facility via a
19 common Ethernet-compatible transmission path.
20
- 21 11. The fiber node of claim 7, wherein channel separation is performed prior to the
22 digitizing framer, such that at least one selected channel and only selected channels
23 are communicated with said upstream facility.
24
25

- 1 12. The fiber node of claim 11, wherein the channel separation is performed in the digital
2 domain after analog-to-digital conversion.
3
- 4 13. The fiber node of claim 12, wherein the digitized modulated signal data is
5 compressed prior to being communicated to said upstream facility.
6
- 7 14. The fiber node of claim 9, wherein reconstruction of the digitized modulated signals
8 is performed at the upstream facility.
9
- 10 15. The fiber node of claim 12, wherein a plurality of selected non-contiguous channels
11 having respective modulated signals are concurrently separated and framed, merged
12 together for communication over a common Ethernet-compatible transmission path,
13 and subsequently separated and concurrently reconstructed at the upstream facility.
14
- 15 16. The fiber node of claim 15, wherein the upstream facility is a head end.
16
- 17 17. The fiber node of claim 16, wherein the cable modems are compatible with the
18 DOCSIS standard and the modulated signals are legacy telephone signals.
19
- 20 18. The fiber node of claim 15, wherein the upstream facility is a secondary head end.
21
- 22 19. The fiber node of claim 18, wherein the cable modems are compatible with the
23 DOCSIS standard and the modulated signals are legacy telephone signals.
24

- 1 20. The fiber node of claim 15, wherein the upstream facility is a hub.
2
- 3 21. The fiber node of claim 20, wherein the cable modems are compatible with the
4 DOCSIS standard and the modulated signals are legacy telephone signals.
5
- 6 22. The fiber node of claim 6, wherein the channel separation is performed in the digital
7 domain after analog-to-digital conversion.
8
- 9 23. The fiber node of claim 22, wherein the channel separation is performed by digital
10 receivers with programmable center frequency and bandwidth.
11
- 12 24. The fiber node of claim 23, wherein the receivers are programmed by sending
13 commands to the fiber node via the packet data interface.
14
- 15 25. The fiber node of claim 24, wherein the fiber node is an mFN.
16
- 17 26. The fiber node of claim 1, further including analog combine and split circuitry
18 coupled to the upstream analog RF interface, the downstream analog RF interface,
19 and to the subscriber cable modems.
20
- 21 27. The fiber node of claim 26, wherein the analog combine and split circuitry is coupled
22 to the subscriber cable modems via a coaxial-cable distribution.
23
24
25

- 1 28. A hybrid fiber-coax network (HFCN) system, comprising:
- 2 a) an upstream HFCN facility;
- 3 b) a plurality of subscriber cable modems;
- 4 c) a first plurality of fiber nodes at intermediate points between said upstream
- 5 HFCN facility and said plurality of subscriber cable modems, at least a
- 6 second plurality of said first plurality of fiber nodes have an integral Cable
- 7 Modem Termination System (CMTS), each CMTS communicating with at
- 8 least some of said plurality of cable modems via analog RF, each CMTS
- 9 communicating subscriber cable modem data with said upstream HFCN
- 10 facility via packet data.
- 11
- 12 29. The HFCN system of claim 28, wherein the CMTS comprises:
- 13 a) a packet protocol block having a packet data interface, a transmitter data
- 14 interface, and a receiver data interface, said packet protocol block
- 15 communicating subscriber cable modem data with said upstream HFCN
- 16 facility via said packet data interface;
- 17 b) a plurality of modulators transmitting data to said subscriber cable modems
- 18 via a downstream analog RF interface, said transmitted data being provided
- 19 by said packet protocol block via said transmitter data interface; and
- 20 c) a plurality of demodulators for extracting data from subscriber cable modems
- 21 received via an upstream analog RF interface, said extracted data being
- 22 provided to said packet protocol block via said receiver data interface.
- 23
- 24 30. The HFCN system of claim 29, wherein the cable modems are compatible with the
- 25 DOCSIS standard.

1 31. The HFCN system of claim 29, wherein the upstream facility is a head end.

2

3 32. The HFCN system of claim 29, wherein the upstream facility is a secondary head
4 end.

5

6 33. The HFCN system of claim 29, wherein the upstream facility is a hub.

7

8 34. The HFCN system of claim 29, wherein channel separation is performed prior to the
9 demodulators such that multiple channels are extracted from each physical
10 transmission path of the upstream analog RF interface.

11

12 35. The HFCN system of claim 29, wherein the CMTS further includes at least one
13 digitizing framer for digitizing modulated signals as received via an upstream analog
14 RF interface, said digitized modulated signal data being provided to said packet
15 protocol block via said receiver data interface.

16

17 36. The HFCN system of claim 35, wherein the cable modems are compatible with the
18 DOCSIS standard and the modulated signals are legacy telephone signals.

19

20 37. The HFCN system of claim 35, wherein the extracted data and the digitized
21 modulated signal data are merged in said packet protocol block for communication
22 over a common packet transmission path with the upstream facility.

23

1 38. The HFCN system of claim 36, wherein the extracted DOCSIS cable modem data
2 and the digitized legacy telephone data are communicated with said upstream facility
3 via a common Ethernet-compatible transmission path.
4

5 39. The HFCN system of claim 35, wherein channel separation is performed prior to the
6 digitizing framer, such that at least one selected channel and only selected channels
7 are communicated with said upstream facility.
8

9 40. The HFCN system of claim 39, wherein the channel separation is performed in the
10 digital domain after analog-to-digital conversion.
11

12 41. The HFCN system of claim 40, wherein the digitized modulated signal data is
13 compressed prior to being communicated to said upstream facility.
14

15 42. The HFCN system of claim 37, wherein reconstruction of the digitized modulated
16 signals is performed at the upstream facility.
17

18 43. The HFCN system of claim 40, wherein a plurality of selected non-contiguous
19 channels having respective modulated signals are concurrently separated and framed,
20 merged together for communication over a common Ethernet-compatible
21 transmission path, and subsequently separated and concurrently reconstructed at the
22 upstream facility.
23

24 44. The HFCN system of claim 43, wherein the upstream facility is a head end.
25

- 1 45. The HFCN system of claim 44, wherein the cable modems are compatible with the
2 DOCSIS standard and the modulated signals are legacy telephone signals.
3
- 4 46. The HFCN system of claim 43, wherein the upstream facility is a secondary head
5 end.
6
- 7 47. The HFCN system of claim 46, wherein the cable modems are compatible with the
8 DOCSIS standard and the modulated signals are legacy telephone signals.
9
- 10 48. The HFCN system of claim 43, wherein the upstream facility is a hub.
11
- 12 49. The HFCN system of claim 48, wherein the cable modems are compatible with the
13 DOCSIS standard and the modulated signals are legacy telephone signals.
14
- 15 50. The HFCN system of claim 34, wherein the channel separation is performed in the
16 digital domain after analog-to-digital conversion.
17
- 18 51. The HFCN system of claim 50, wherein the channel separation is performed by
19 digital receivers with programmable center frequency and bandwidth.
20
- 21 52. The HFCN system of claim 51, wherein the receivers of each CMTS are programmed
22 by sending commands to the respective packet data interface of each CMTS.
23

1 53. The HFCN system of claim 52, wherein at least one of fiber nodes having a CMTS is
2 an mFN.

3

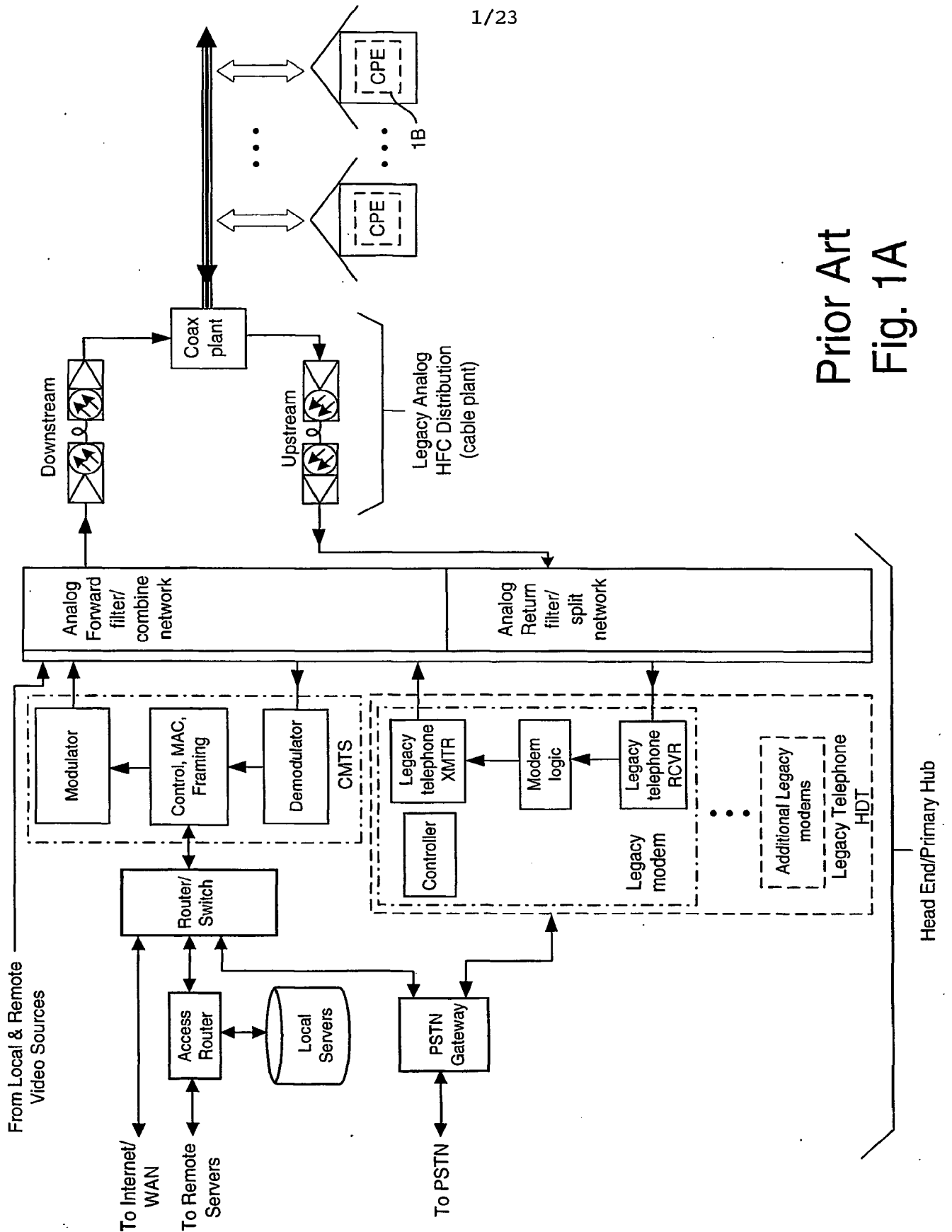
4 54. The HFCN system of claim 29, further including analog combine and split circuitry
5 coupled to the upstream analog RF interface, the downstream analog RF interface,
6 and to the subscriber cable modems.

7

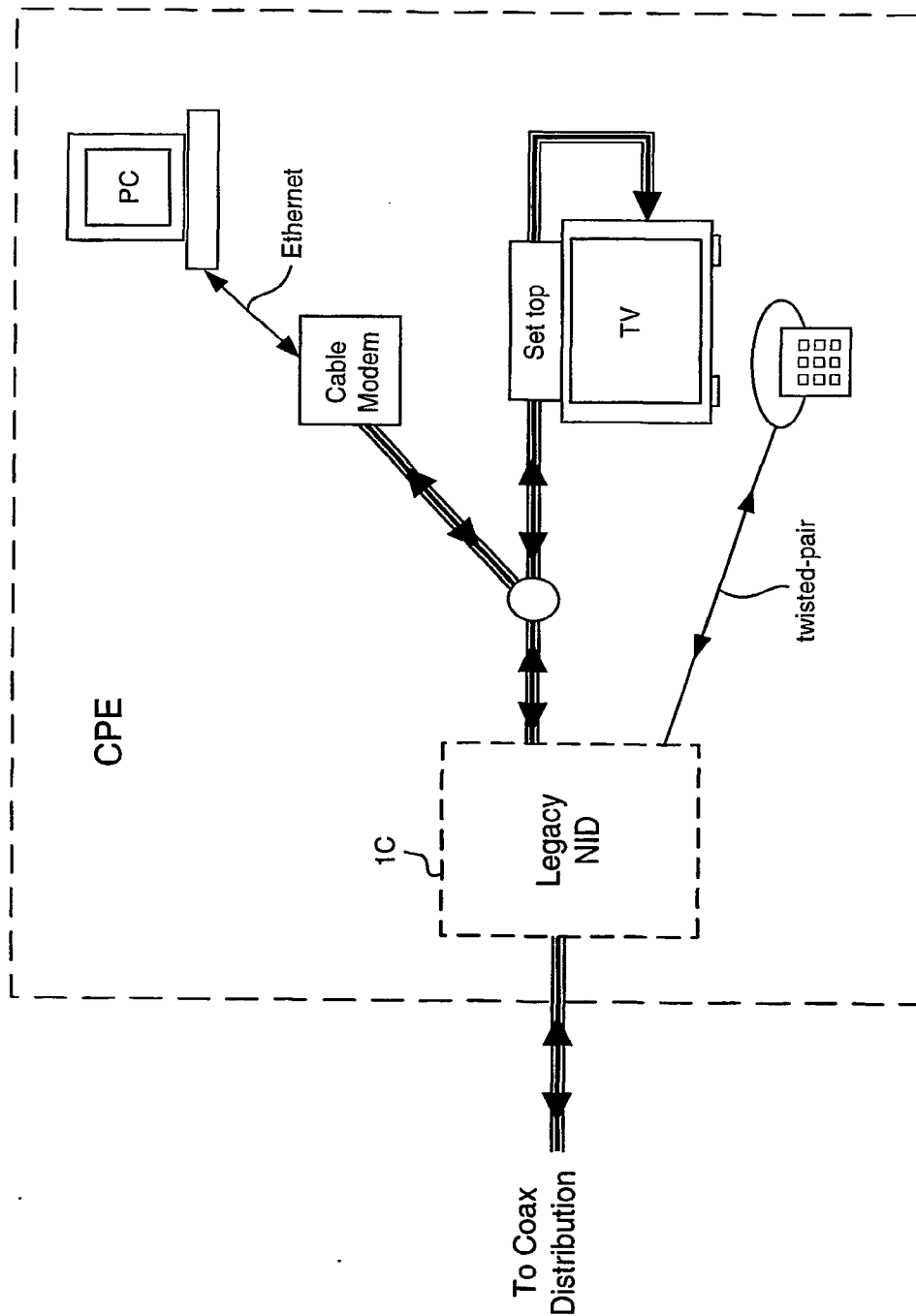
8 55. The HFCN system of claim 54, wherein the analog combine and split circuitry is
9 coupled to the subscriber cable modems via a coaxial-cable distribution.

10

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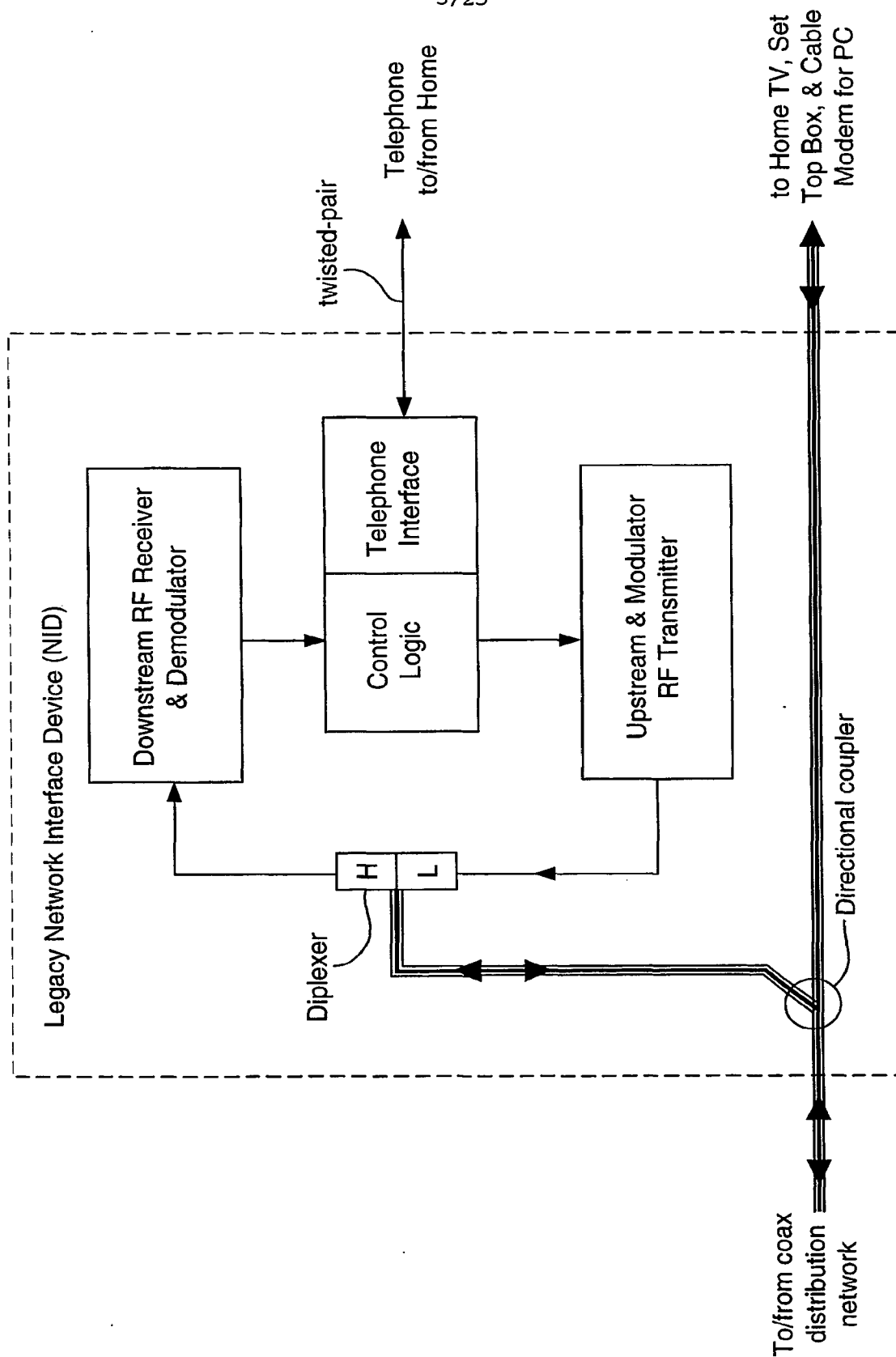


Prior Art
Fig. 1A

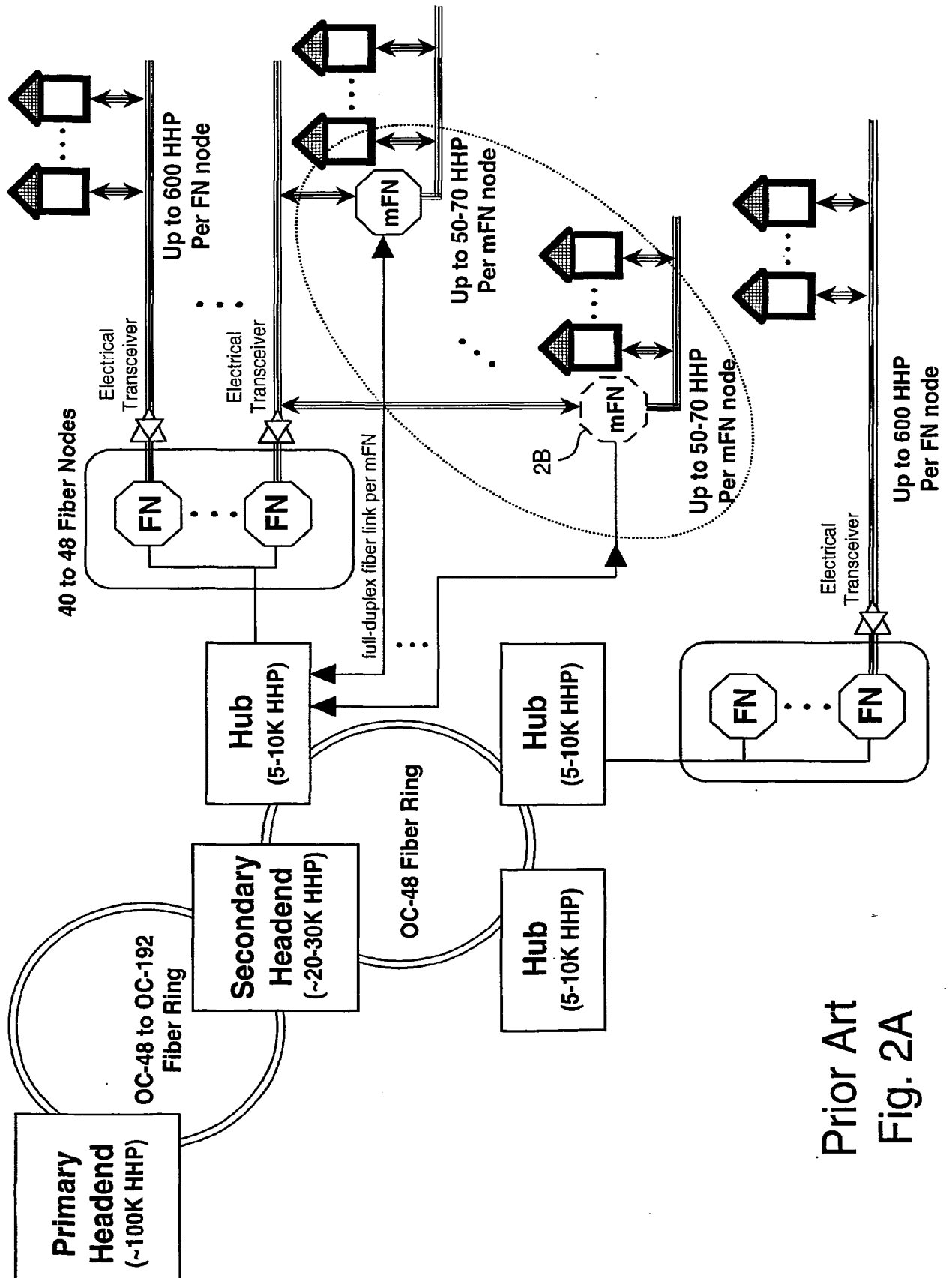


Prior Art
Fig. 1B

3/23

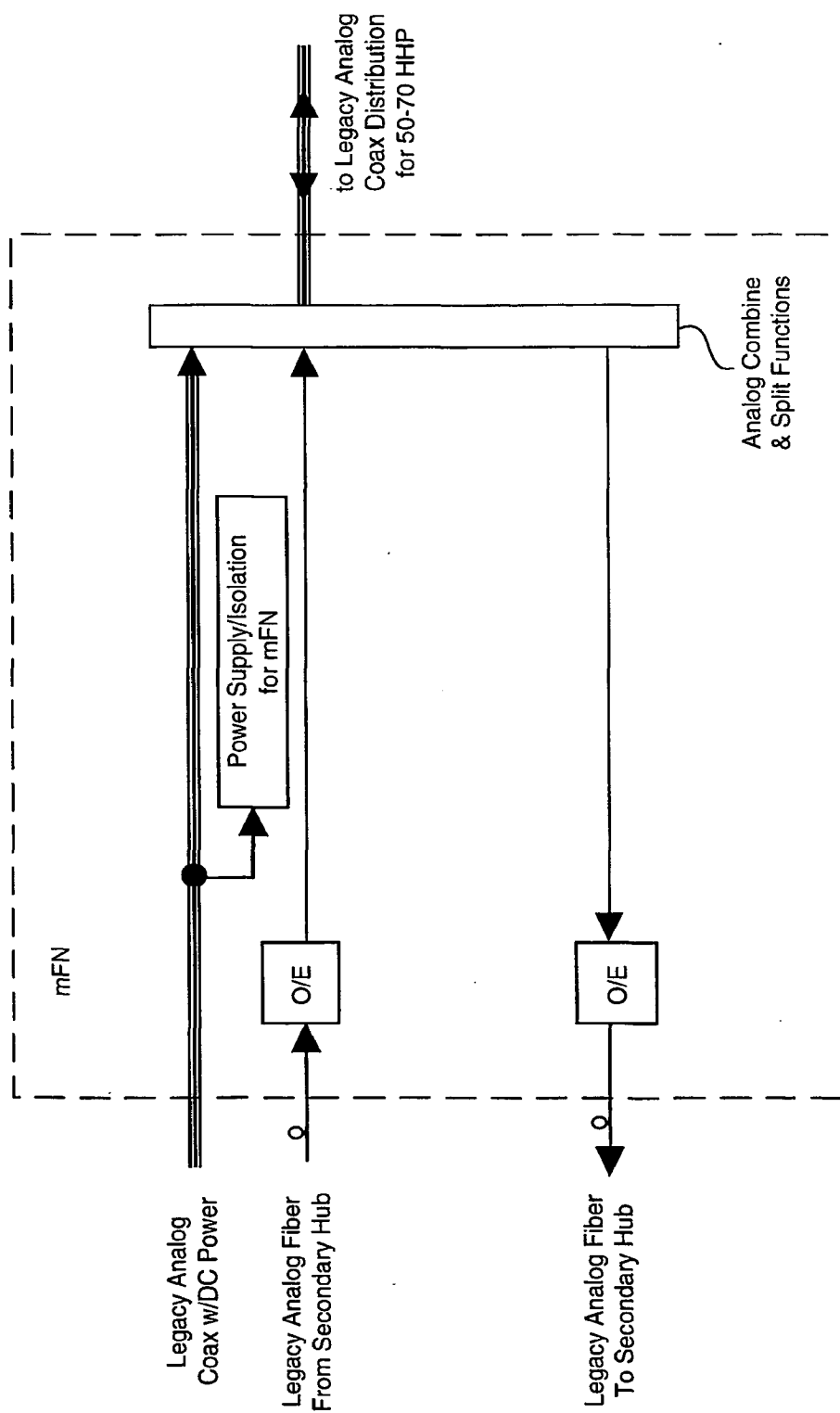


Prior Art
Fig. 1C



Prior Art
Fig. 2A

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Prior Art
Fig. 2B

6/23

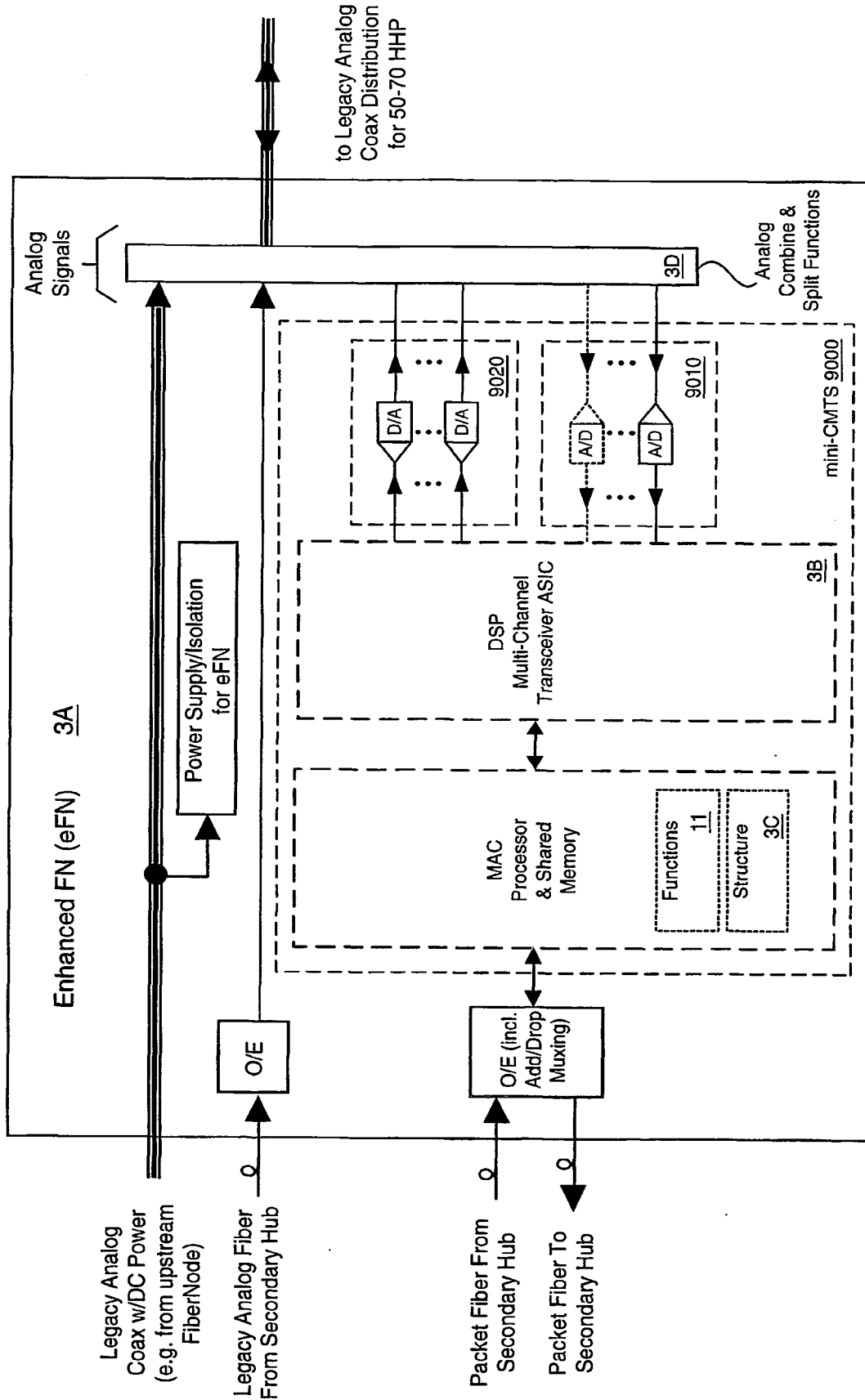


Fig. 3A

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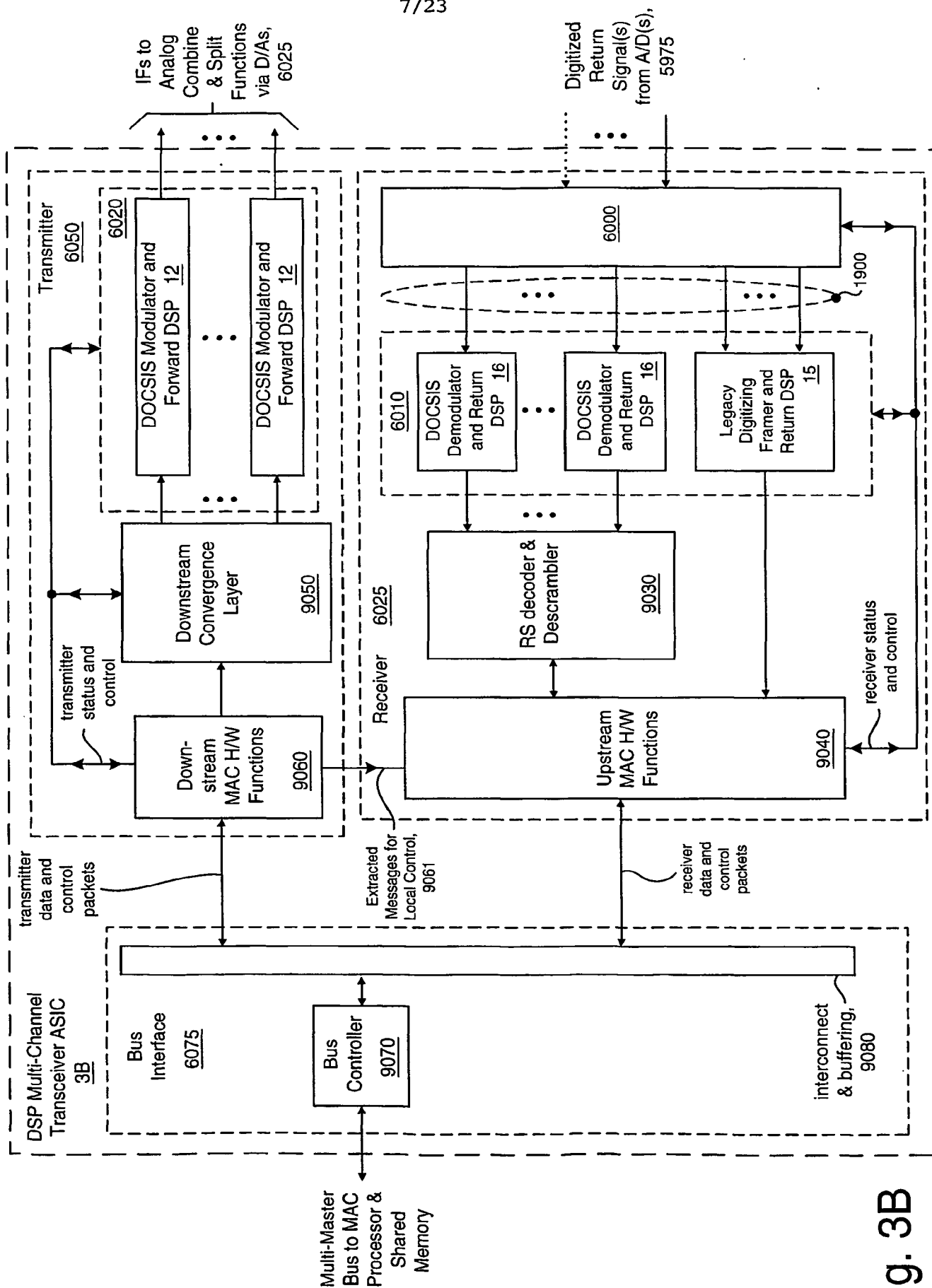


Fig. 3B

8/23

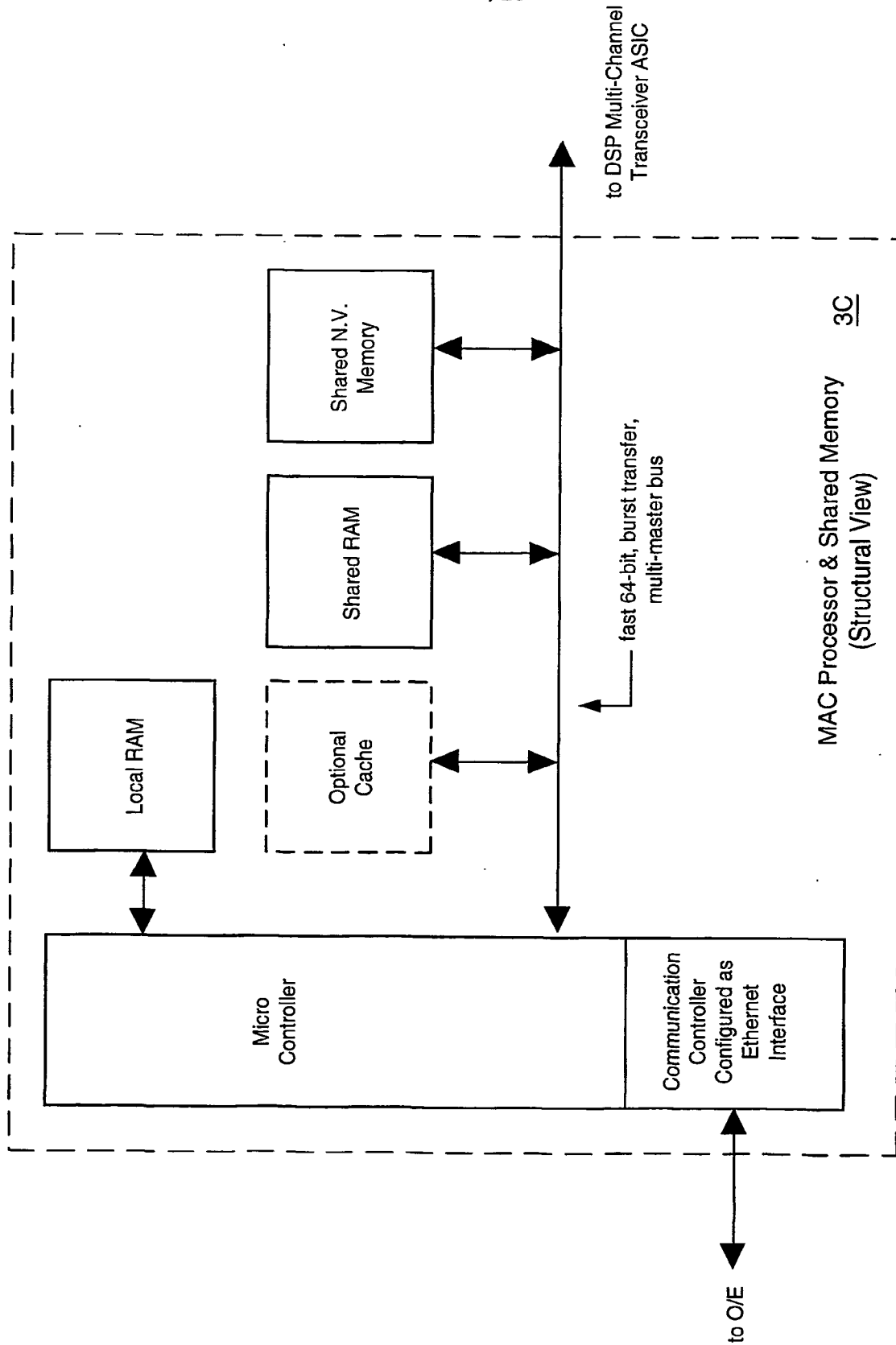


Fig. 3C

9/23

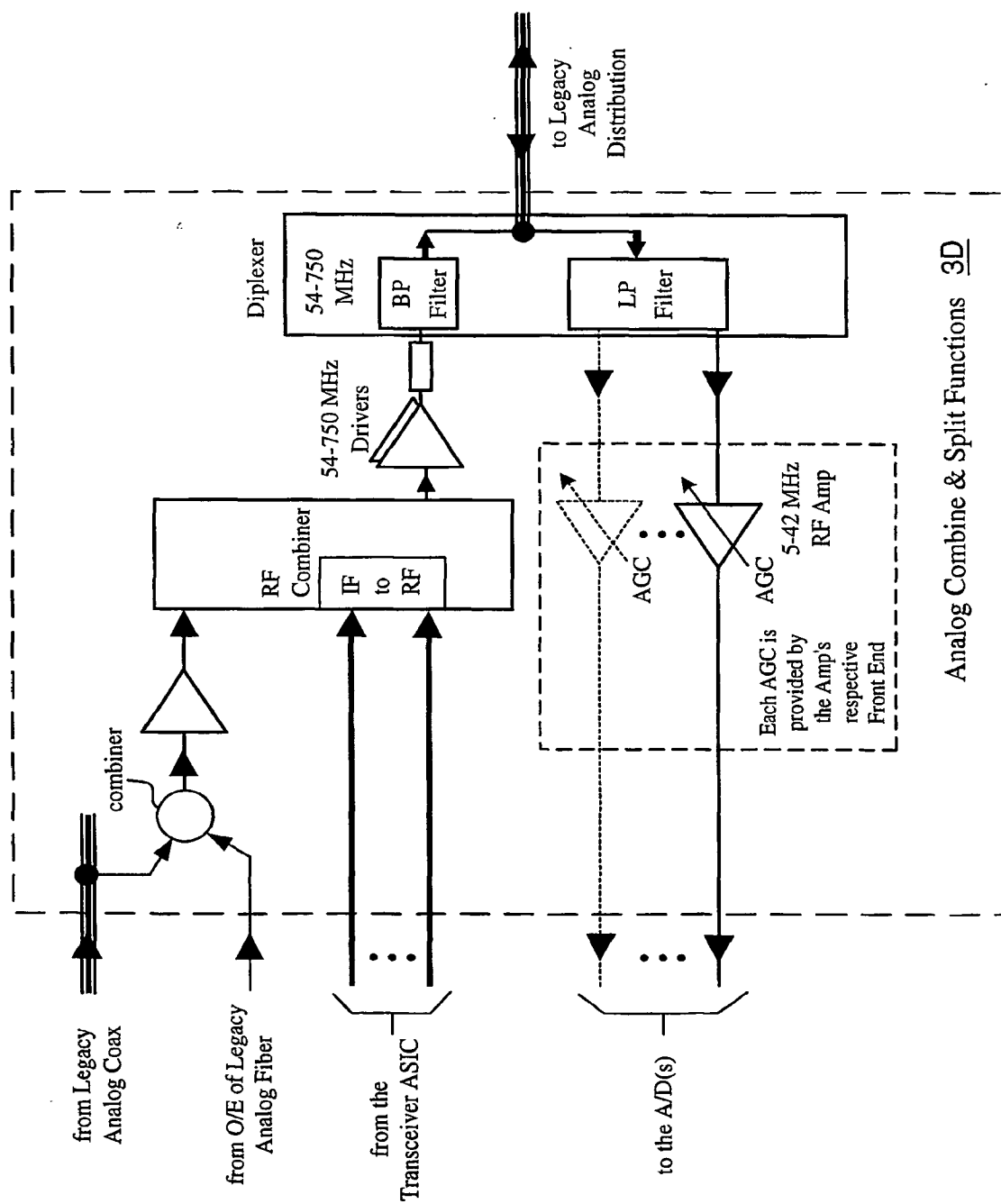
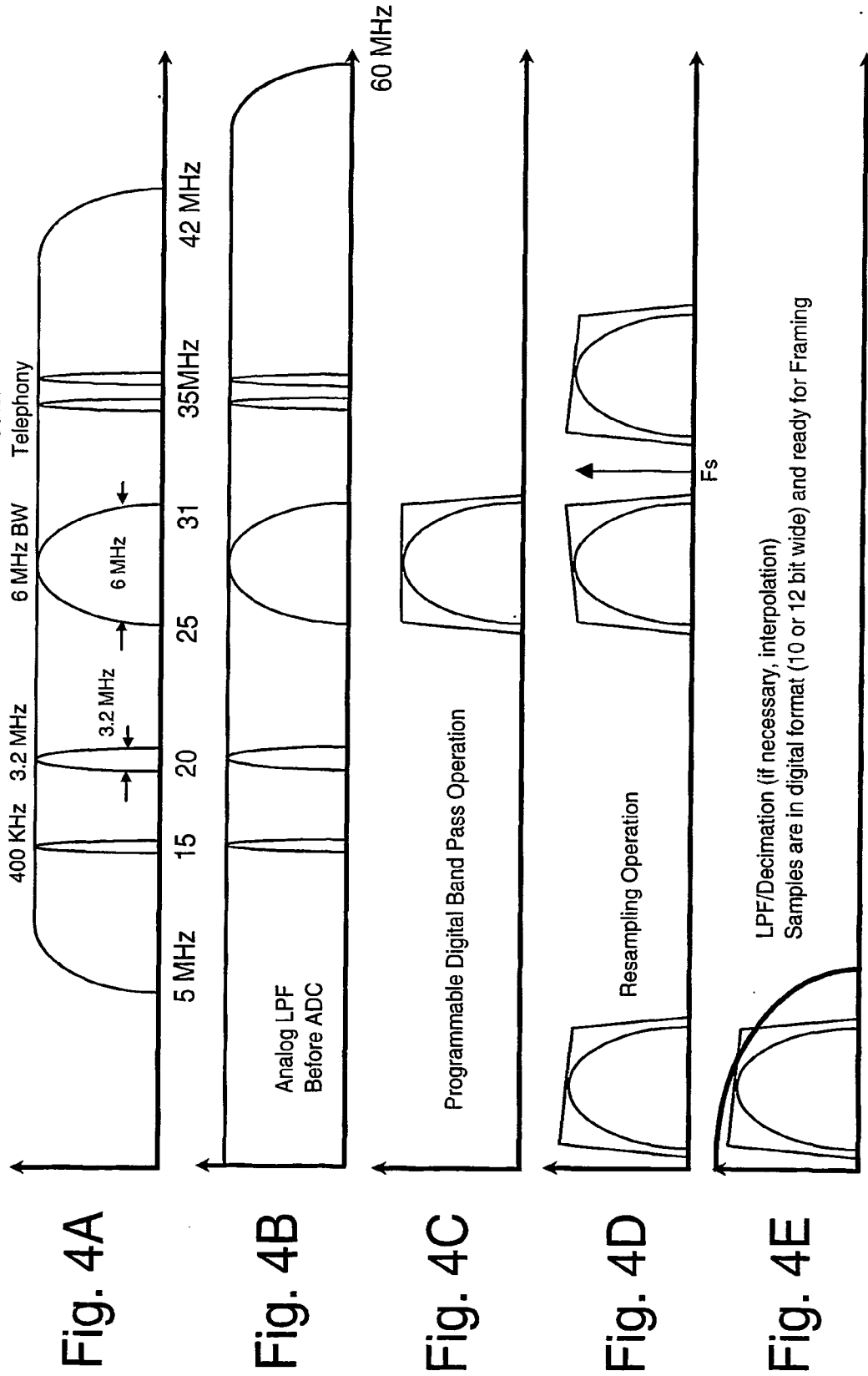


Fig. 3D

10/23



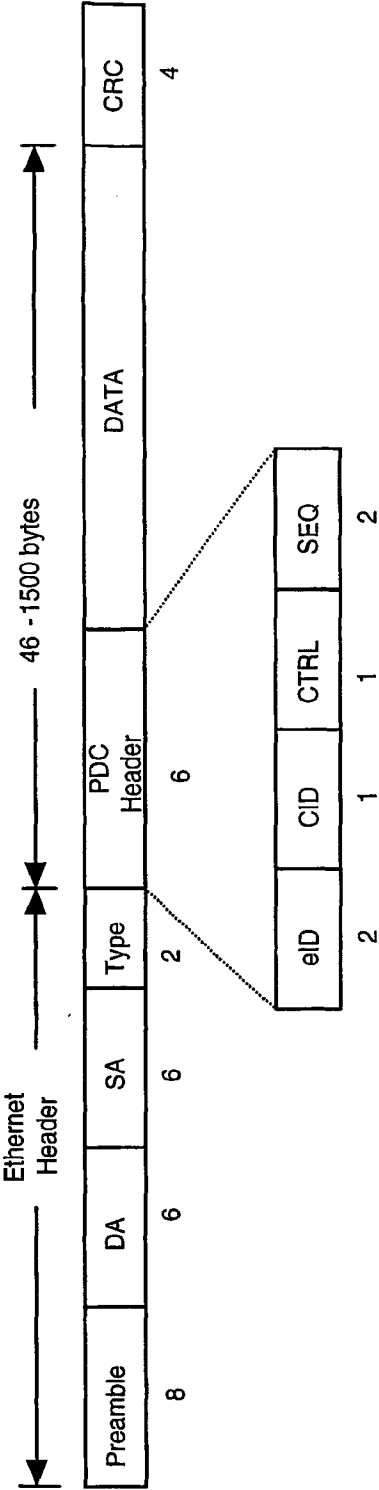


Fig. 5

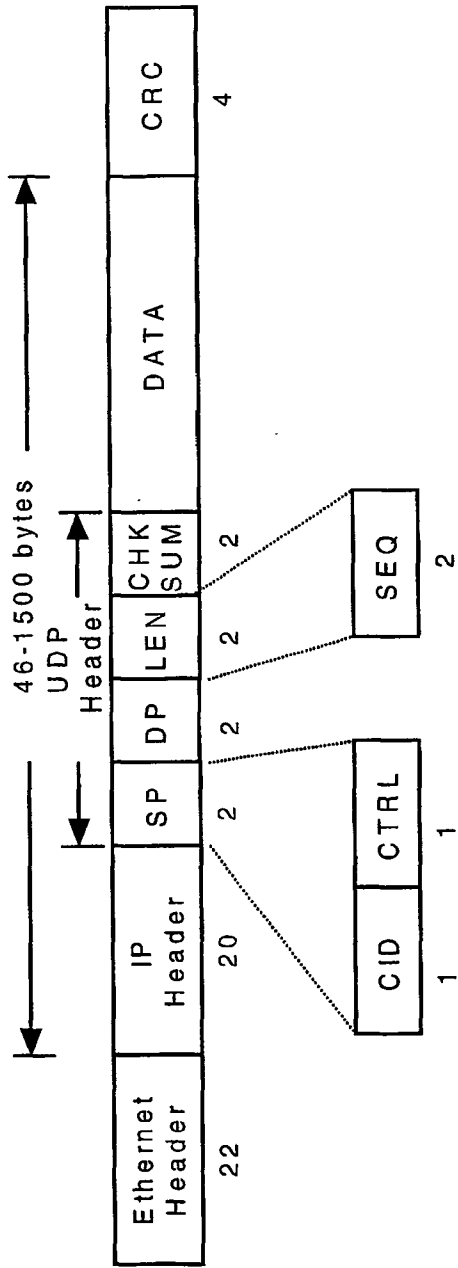


Fig. 6

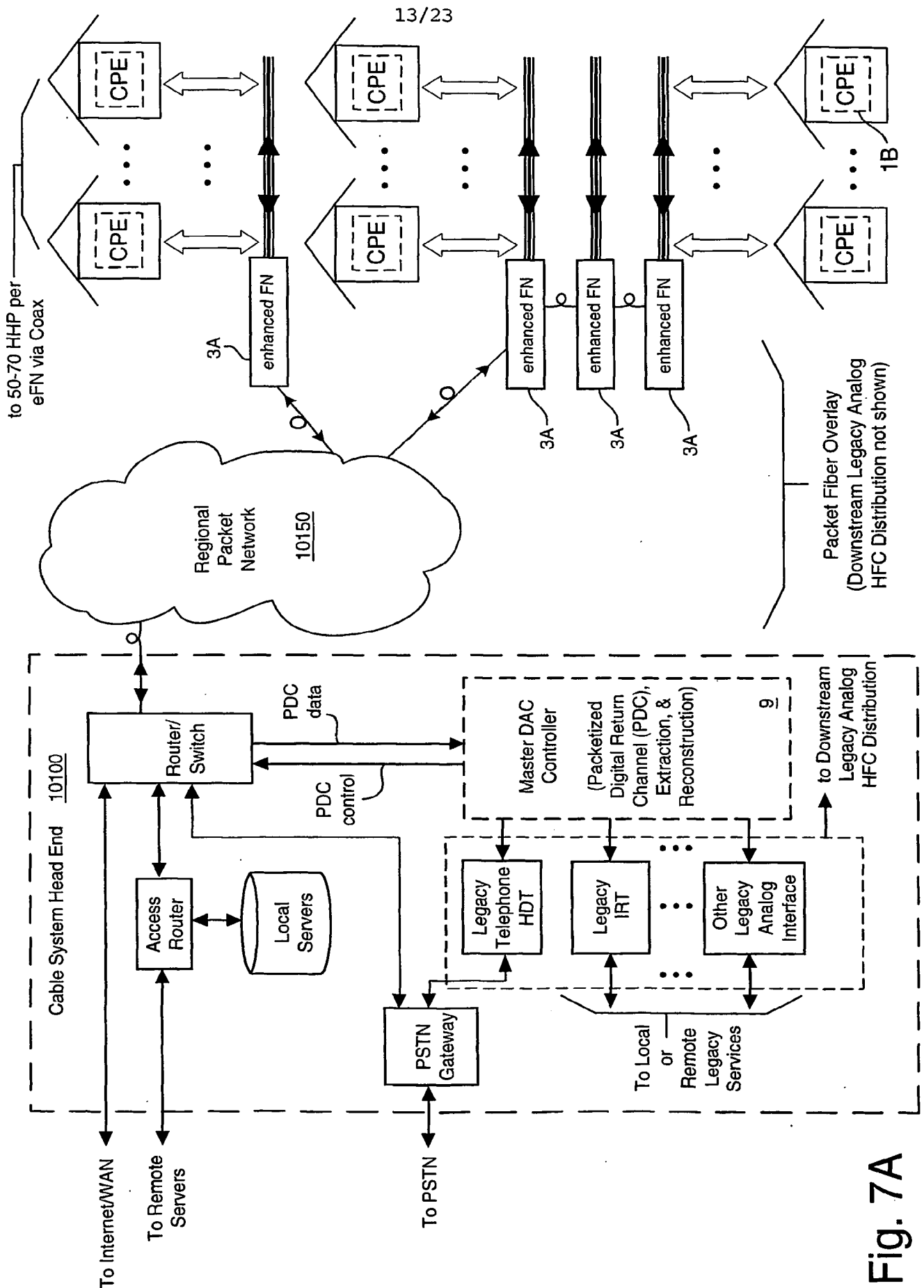


Fig. 7A

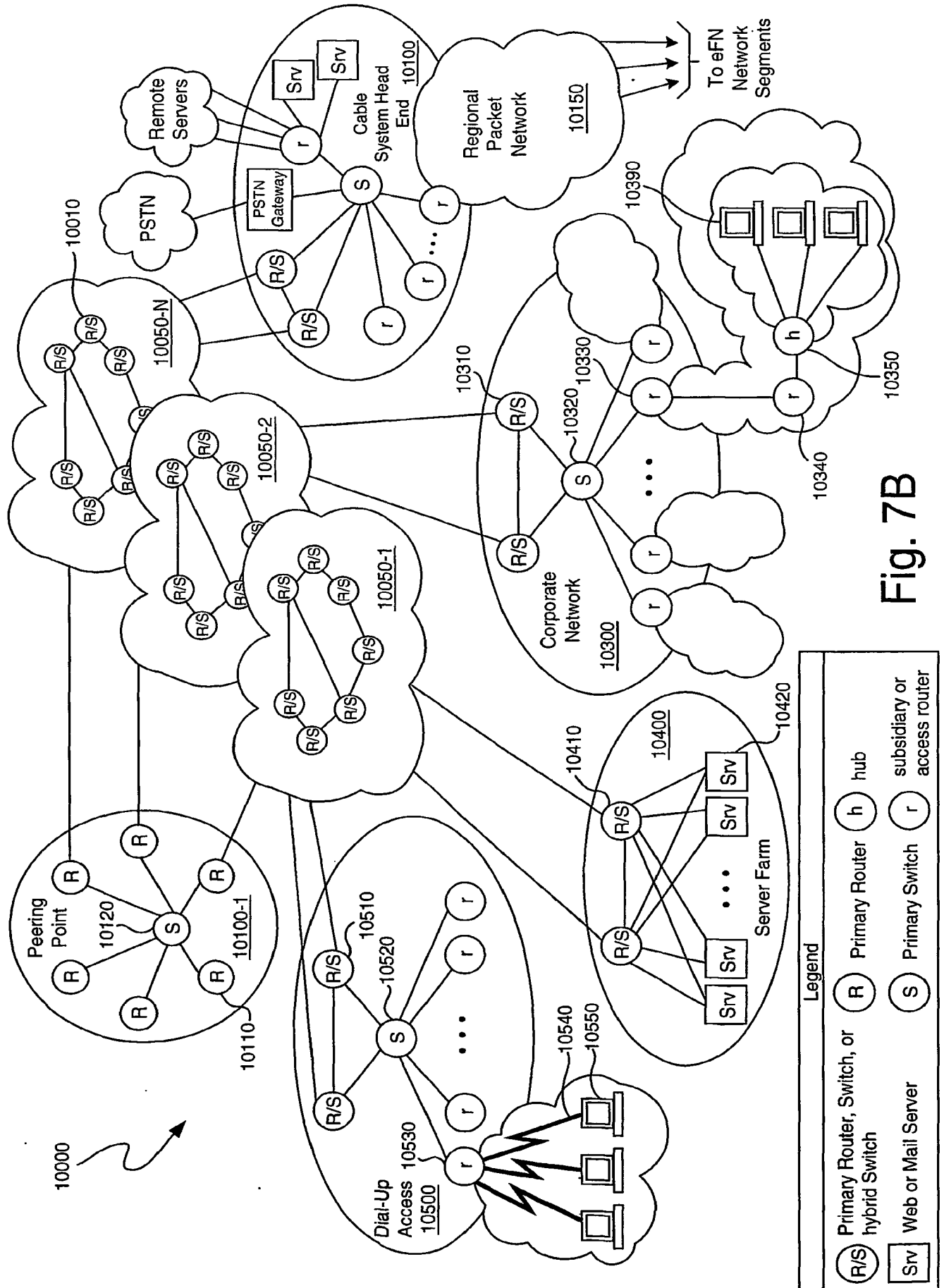


Fig. 7B

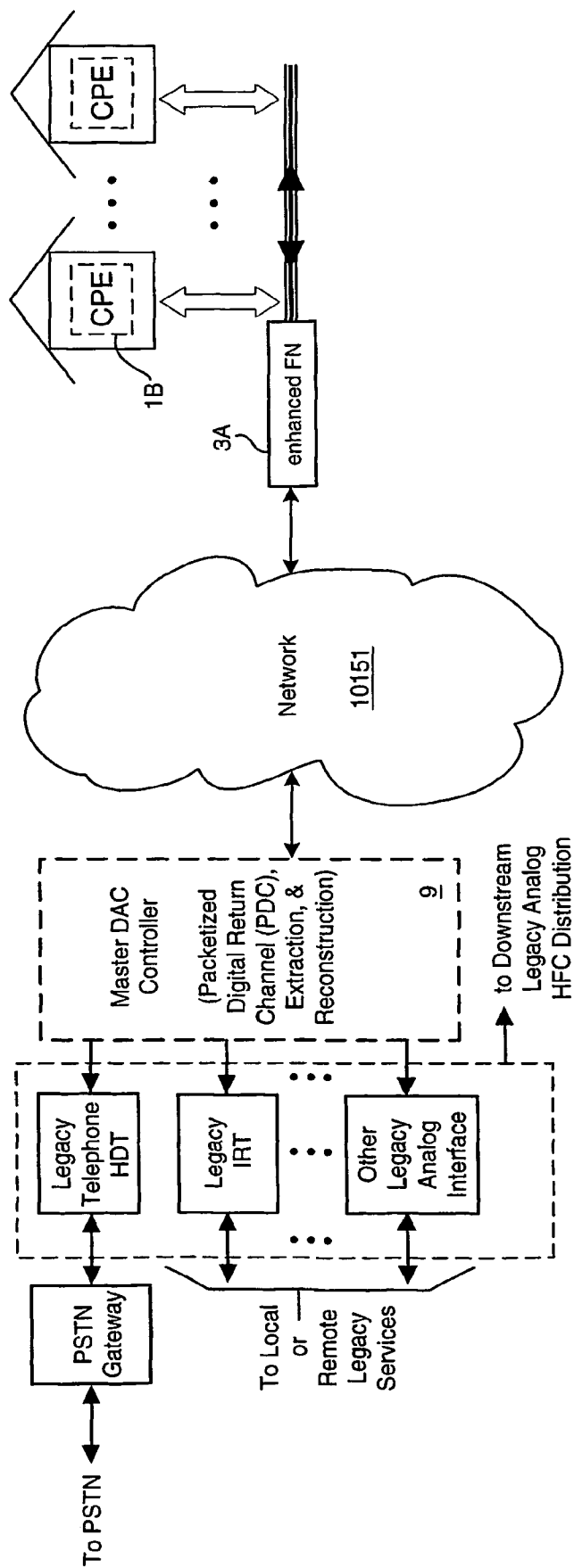


Fig. 7C

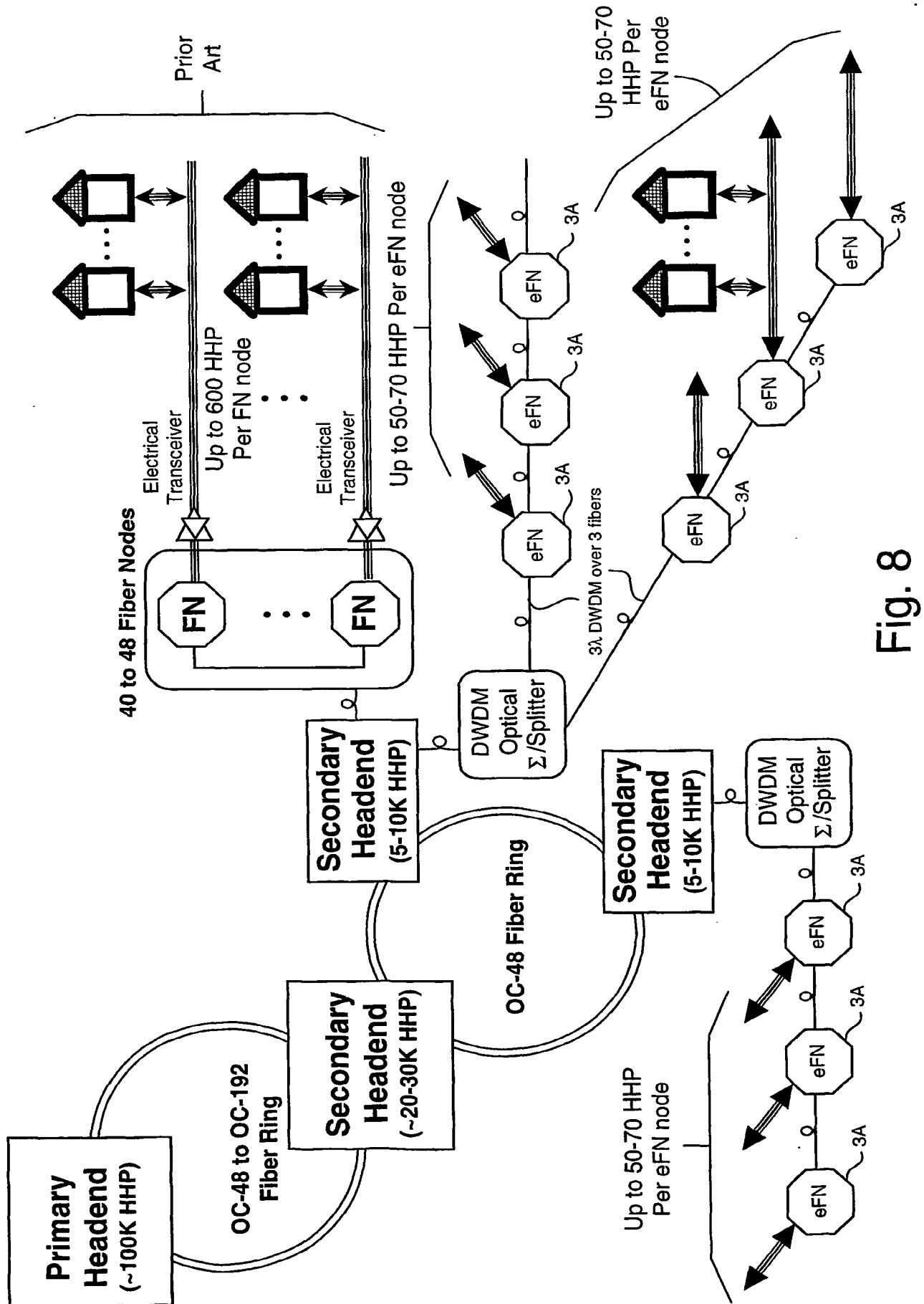


Fig. 8

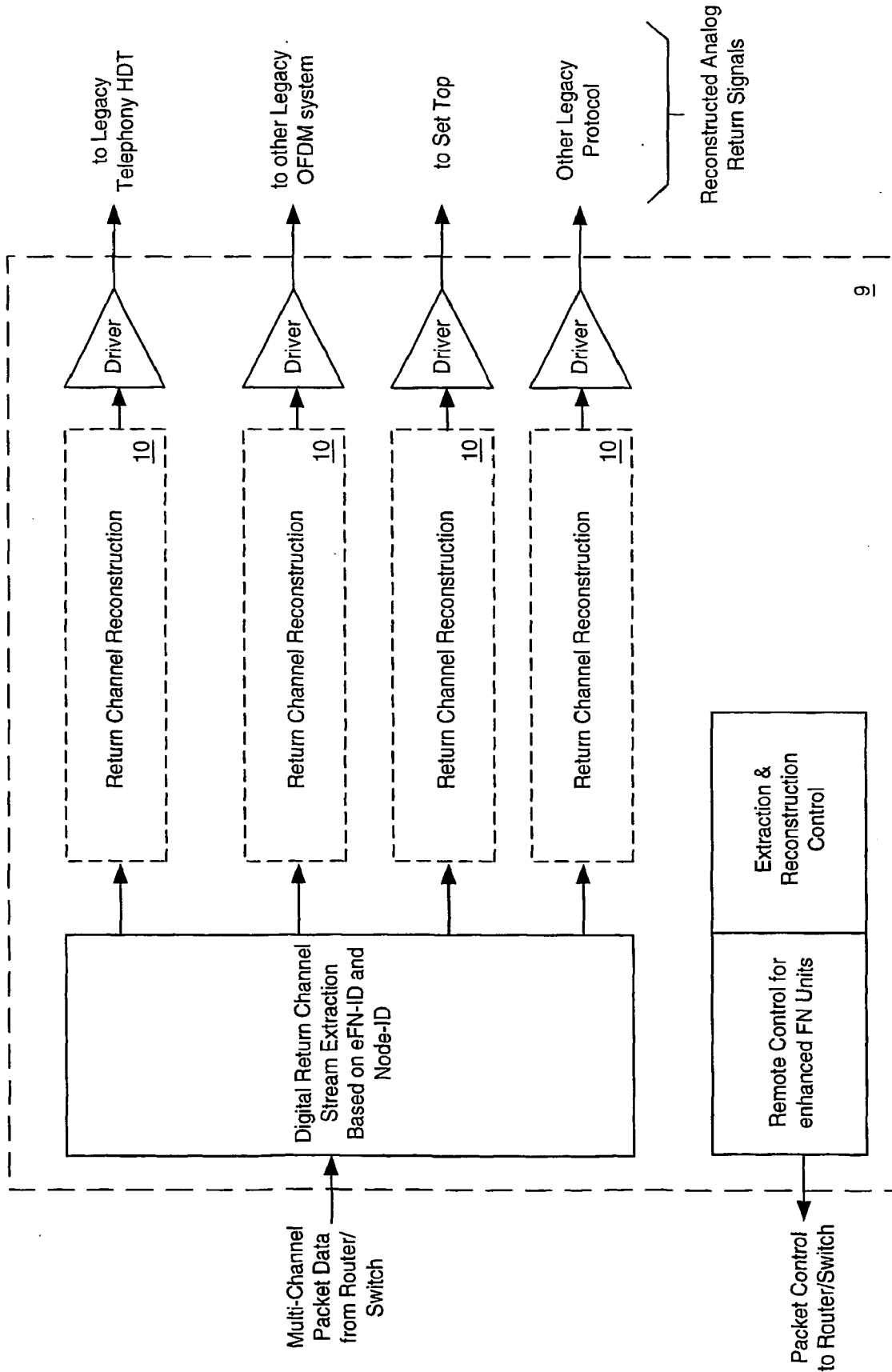


Fig. 9

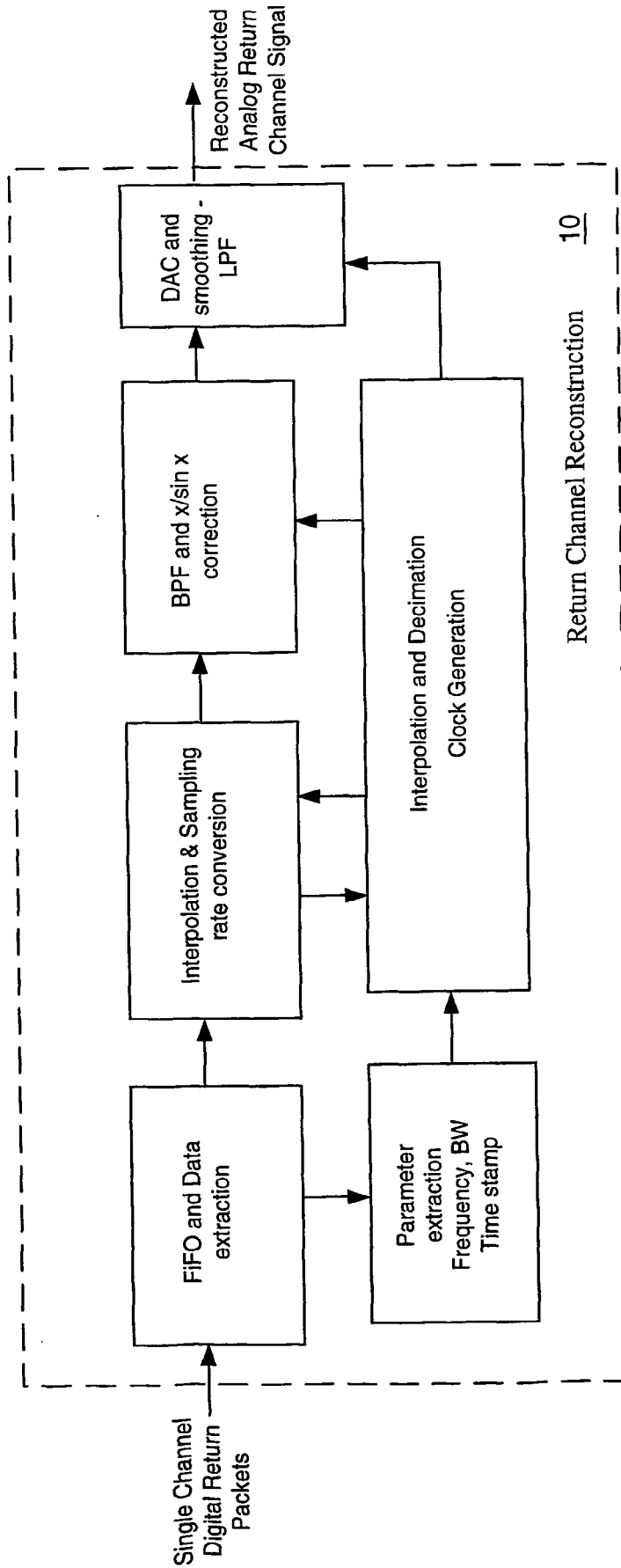


Fig. 10

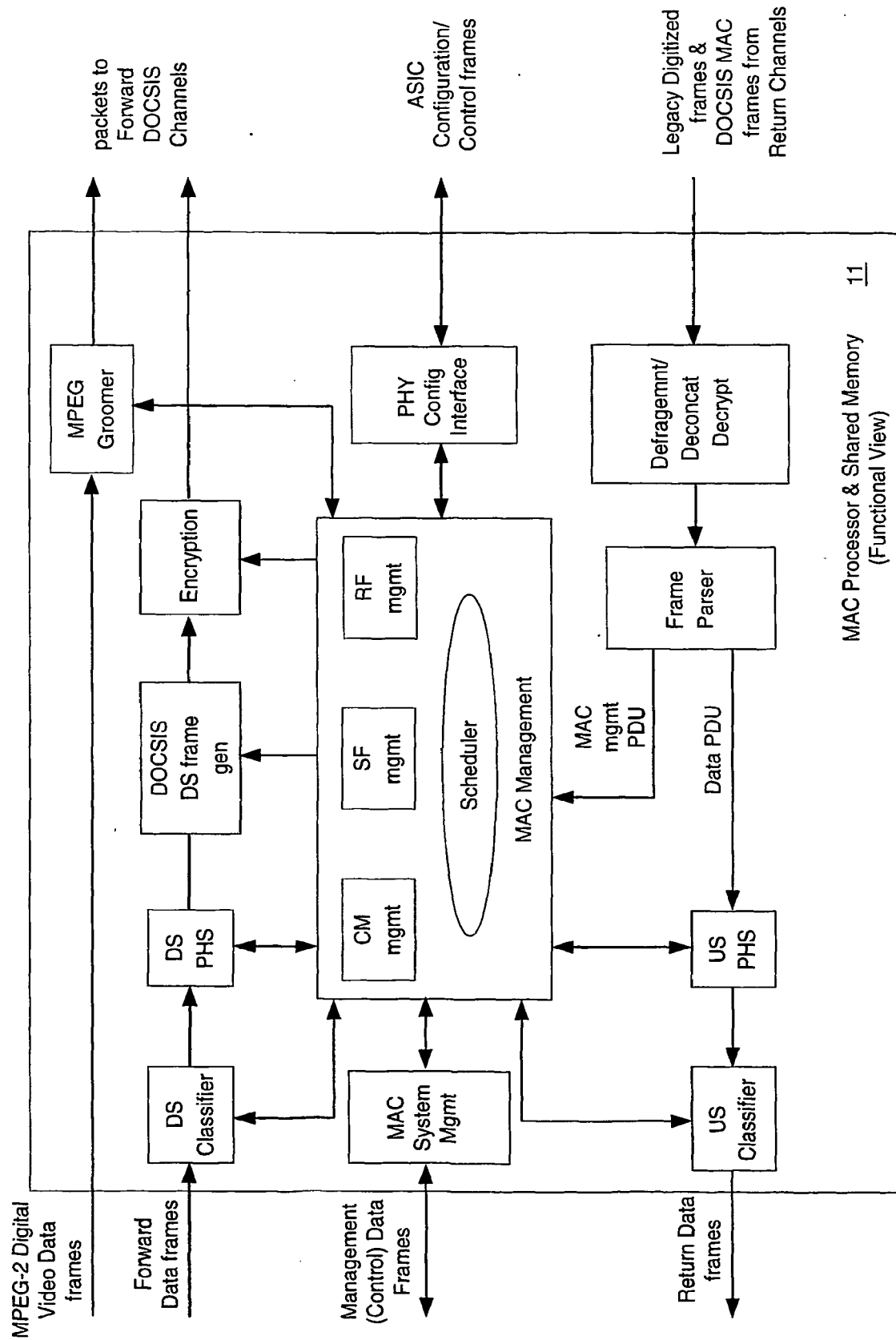


Fig. 11

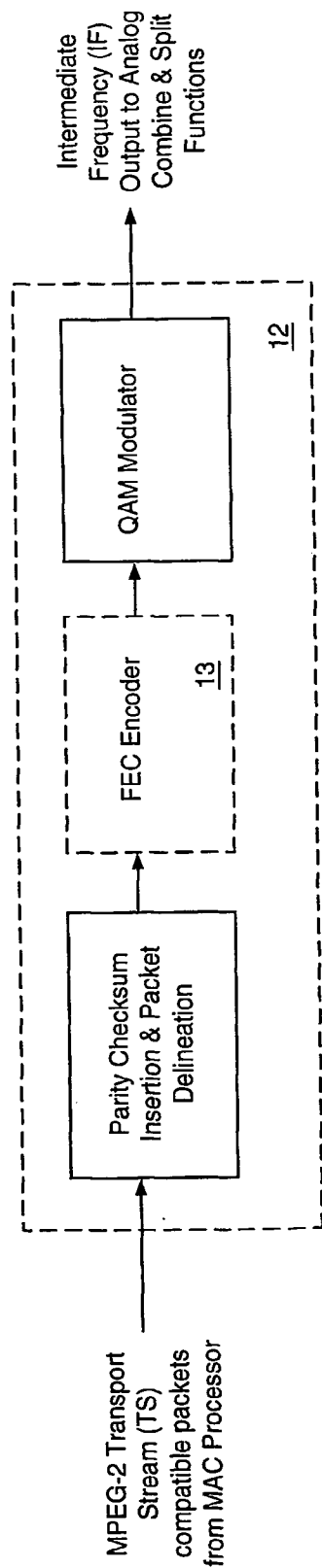


Fig. 12

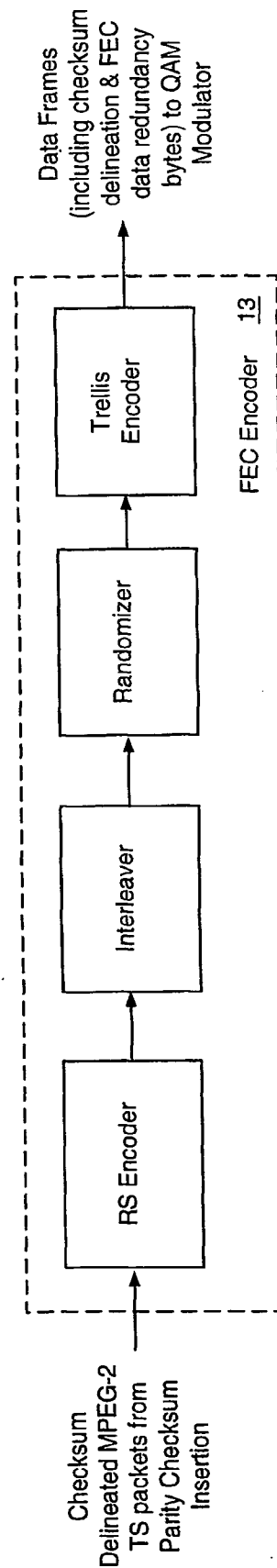


Fig. 13

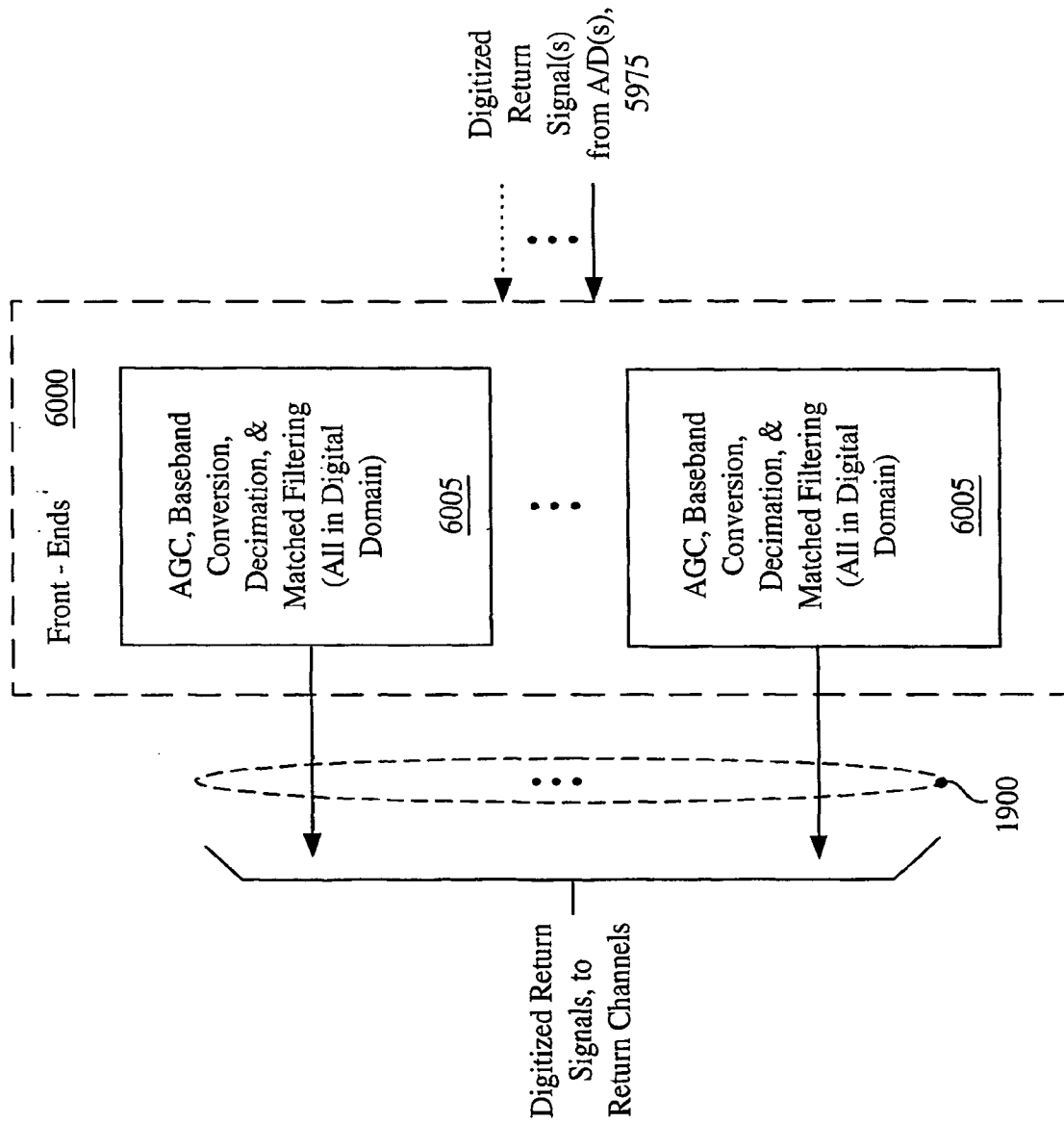


Fig. 14

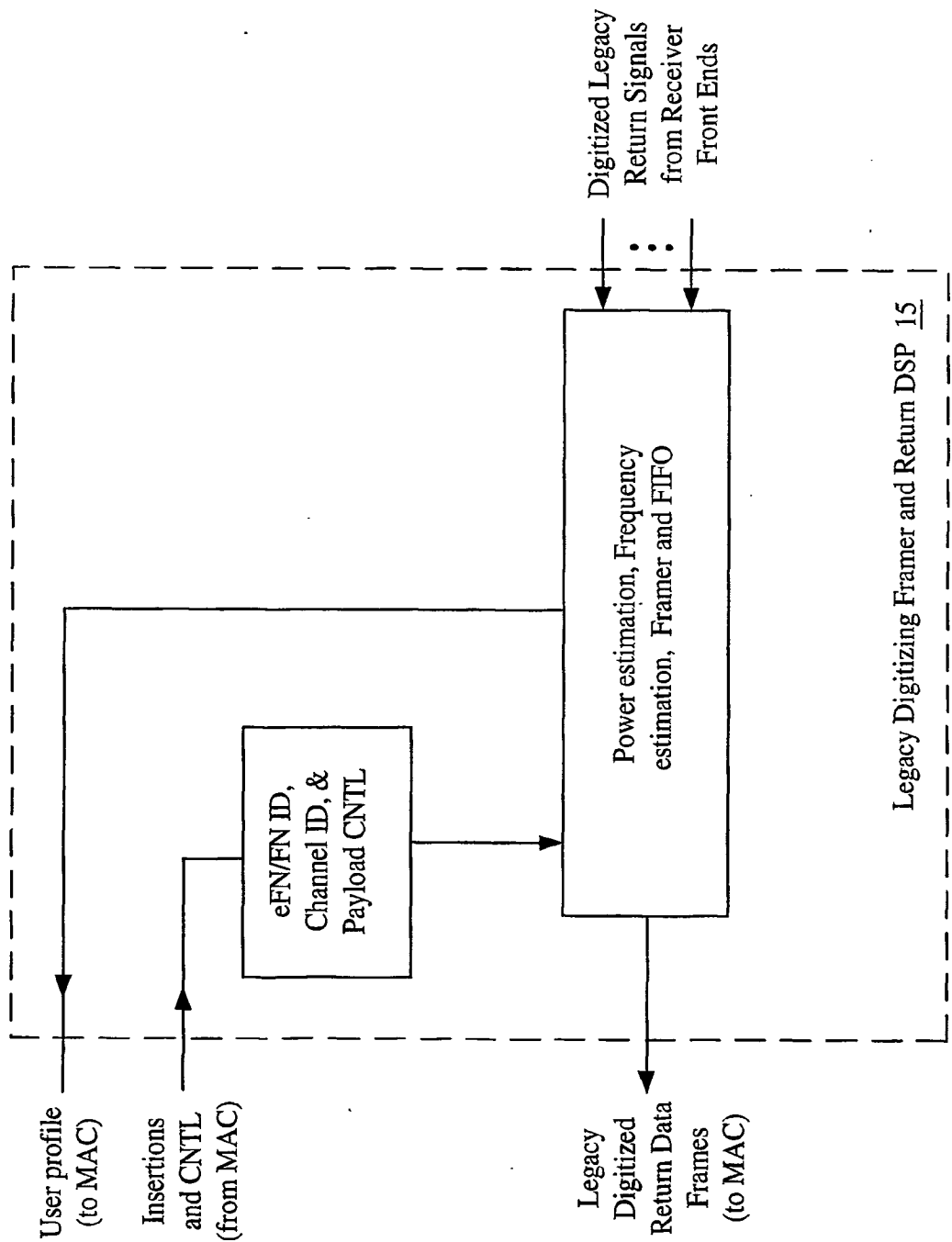


Fig. 15

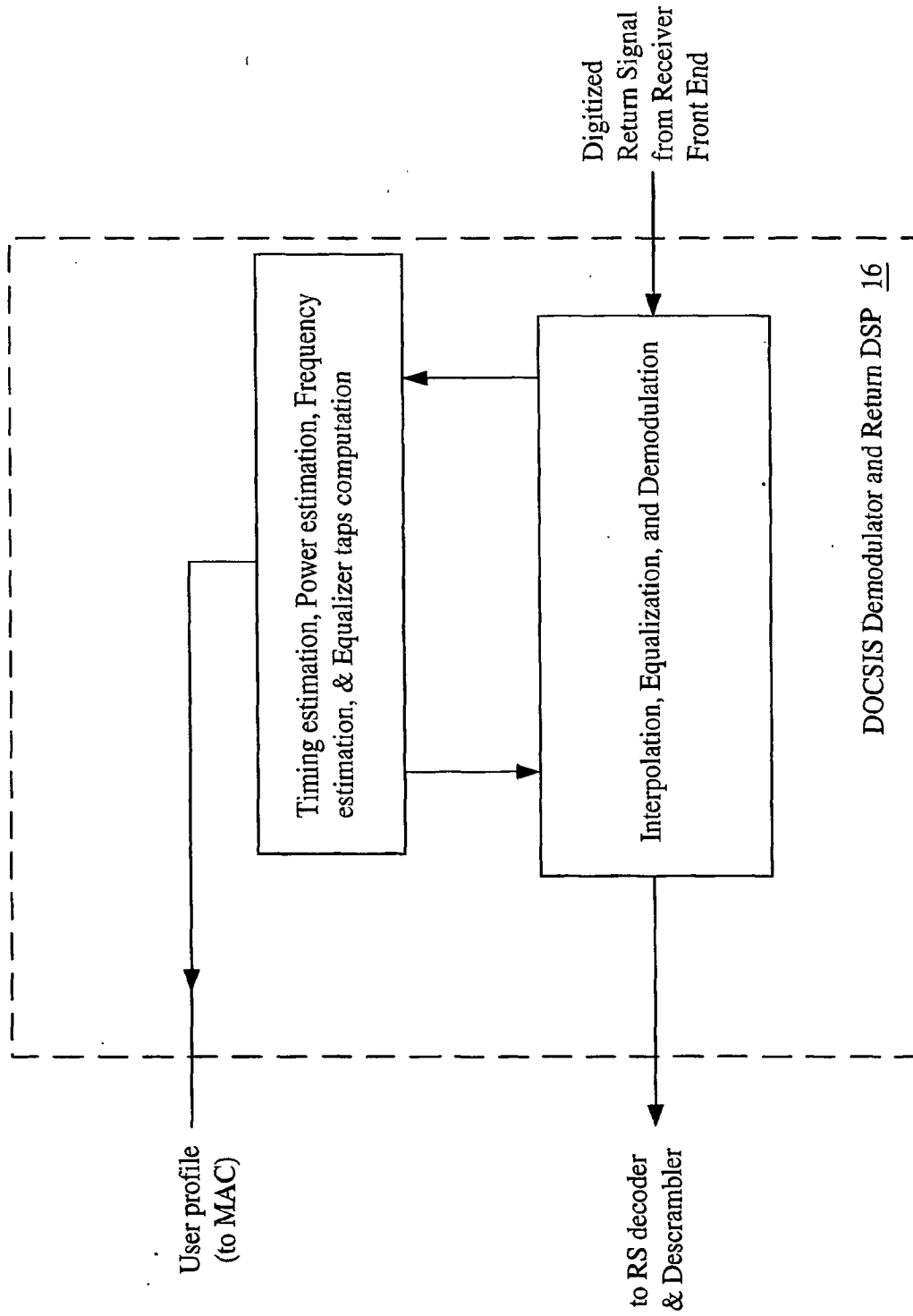


Fig. 16

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